

On the causes and modes of exhumation and lateral growth of the Alps

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[1] A compilation of the apatite and zircon fission track ages of the Alpine chain points to markedly different patterns of cooling and exhumation of the Eastern Alps compared to the central and Western Alps. The site of exhumation and shortening in the Western Alps migrated outward, whereas it was more stationary in the Eastern Alps, where it created a narrower metamorphic belt. A correlation of these observations to the deep structure of the orogen suggests that north directed, lower crustal wedging induces northward propagation of the deformation and exhumation front in the middle and upper crust of the central and Western Alps. The absence of such lower crustal wedges in the Eastern Alps does not induce a similar shift of deformation but rather a long-term localization of shortening and exhumation in one and the same area, namely, the axial zone of the orogen. A critical review of the temporal correlations between inferred changes in the erosional efficiency of the Alps and tectonic phases points to a negative correlation, and hence no erosional control on the shifts of the deformation front of the Alps. Therefore, we conclude that changes in the deep structure and rheology of the orogen, instead of changes in its erosional efficiency, exerted the prime control on the lateral growth of the Alps. **Citation:** Rosenberg, C. L., and A. Berger (2009), On the causes and modes of exhumation and lateral growth of the Alps, *Tectonics*, 28, TC6001, doi:10.1029/2008TC002442.

1. Introduction

[2] Geodynamical models of convergent orogens convincingly show that erosion exerts a major control on the style of deformation of growing mountain chains [Beaumont *et al.*, 1992, 2000; Avouac and Burov, 1996; Willett, 1999] and more importantly on the sites of the long-term localization of shortening and exhumation. Fast erosion rates efficiently remove part of the incoming mass that builds the growing orogen, balancing the addition of new material and eventually attaining a steady state [Bernet *et al.*, 2001; Willett

and Brandon, 2002]. Under these conditions shortening is expected to remain localized in the same area. In contrast, a reduction of the erosional efficiency leads to an increase of accreted mass in the orogen, resulting in its outward growth [Willett *et al.*, 2006]. However, lateral growth may also result from changes in the rheology of the crust and in particular of the upper plate of convergent systems [Doglioni *et al.*, 2007]. As predicted by the theory of critical wedges [Dahlen, 1984], the basal friction of the wedge controls its taper angle, hence its length. High basal friction promotes narrower orogens [e.g., Konstantinovskaia and Malavieille, 2005], resulting in similar geometries as those induced by high erosion rates. The viscosity of the ductile crust and its coupling to the brittle crust also control the sequence of thrust nucleation in space and time. Low viscosities may cause changes from lateral growth during in-sequence thrusting to lateral retreat during out-of-sequence thrusting [Smit *et al.*, 2003].

[3] The strength of the basal layer in natural accretionary wedges is controlled by the rock composition, the fluid content, the temperature and by the strain rate. The latter is expected to drop after the onset of collision. For example, in the Alpine orogen, strain rate apparently dropped after the onset of collision due to decreasing convergence rates [Schmid *et al.*, 1996; Schmid and Kissling, 2000]. This, combined with increasing temperature after crustal thickening [e.g., Berger and Bousquet, 2008; Bousquet *et al.*, 2008] results in decreasing viscosity of the ductile layers, which likely played a role in increasing the width of the orogen. As this example indicates, several factors other than erosion can influence the onset and amount of lateral growth and it is thus difficult to isolate the specific effect of varying erosional efficiency.

[4] Attempts to recognize the long-term effects of changing erosional efficiency on the lateral growth of mountain chains concentrated mainly on the Alps [Schlunegger, 1999; Schlunegger and Willett, 1999; Schlunegger and Simpson, 2002; Bernet *et al.*, 2001; Kuhleemann *et al.*, 2006; Cederbom *et al.*, 2004; Willett *et al.*, 2006]. These investigations attributed lateral shifts in the width of the orogen to climatically induced variations of erosion rates, ignoring the possible, coeval effects of changes in the rheology and in the configuration of the deep crust.

[5] In order to explore the causes of lateral growth of the Alps, evaluating to which degree surface and/or deep-seated processes exert the prime control on the width of the orogen, we attempt to deconvolve the relative roles of these concomitant processes in different areas along the length of the Alps. We first critically review the temporal correlations between tectonic events, changes in the distance between

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the orogen fronts in different parts of the Alps, and changes in the erosional efficiency of the Alps. In a second step, we compare the amount of bulk shortening and the cooling patterns in the Eastern and central Alps, and relate the differences in these patterns with the configuration of the deep crust of the Eastern and the central/Western Alps. Because the Alps are one of the smallest orogens of the Earth, they are particularly suited to test the effect of climate-controlled erosional efficiency on their lateral growth history. Climatic effects should act on the entire length of such a small chain, inducing coeval and similar tectonic, hence exhumational responses in different parts of the orogen. In contrast, if the orogen fronts and the area of maximum exhumation are shifted at different times in different parts of the chain, these shifts may be attributed to local tectonic events and/or deep-seated structural changes, rather than to changes of climate and surface processes.

[6] In addition, the Alps are one of the best investigated orogens, whose surface (Figure 1) and deep structure (Figure 2) [e.g., Schmid *et al.*, 1996; Pfiffner *et al.*, 2002; Schmid *et al.*, 2004] and exhumation history [Handy and Oberhänsli, 2004; Vernon *et al.*, 2008; Garzanti and Malusà, 2008; Luth and Willingshofer, 2008] are well constrained. The term lateral growth will be used to describe the foreland- and hinterland-directed migration of the deformation front, in a direction perpendicular to the longest axis of the orogen.

2. Absolute Changes of Width of the Alpine Orogen

[7] A prerequisite for understanding the causes of lateral growth and/or retreat of the Alps is the estimate of its past changes in width. We therefore compiled on the basis of literature data the absolute width of the orogen at three different stages from the Oligocene to the present (Figure 3) and the changing location of the inferred active fronts of the orogen for the central and Western Alps during the Tertiary (Figure 4). These compilations indicate that the absolute change of width, defined as the distance between the most external thrusts of the orogen from 32 Ma to the present was modest, amounting to less than 15%. This value lies within the error of estimate, hence it is no sound evidence for a change of width. Uncertainties concerning the dip angle of the Periadriatic Fault in the Miocene can affect the amount of horizontal shortening by 10 km. On the other hand the width of the active orogen, defined as the distance between the most external active thrusts, did increase in the early Miocene (Figure 4). This increase started already in the Oligocene (Figure 4) as also concluded on the basis of sedimentological findings, suggesting a continuous growth of thrusts through the Oligocene–early Miocene interval [Schumacher *et al.*, 1996].

[8] In the late Miocene the active width of the Southern Alps decreased, as documented by an out-of-sequence phase of thrusting (Figures 3 and 4, Lecco thrust [Schönborn, 1992]) younger than the Milan Belt (Figures 1, 3, and 4)

[Schönborn, 1992] and older than Messinian [Schönborn, 1992; Schumacher *et al.*, 1996].

[9] A net increase of width can be assessed in the Western Alps (Figure 2) after 10 Ma [Becker, 2000], when the deformation front jumped by more than 80 km into the foreland forming the Jura Mountains (Figure 1). However, this shift was restricted to the northwestern corner of the Alpine arc and to the uppermost 5 km of crust, laying above the basal Jura detachment, which is rooted 100 km farther south in the basement of the Aar Massif (Figure 1). Therefore, it is only the deformation front of the decoupled, uppermost part of the upper crust that is shifted far into the foreland. The cause of this decoupling and transfer of the thrust front has been repeatedly attributed to a rheological factor, namely, the occurrence of thick and weak, anhydrite layers, which allowed for the localization of shortening below the present Jura Mountains [Laubscher, 1961; Jordan, 1994; Becker, 2000]. The southern and eastern termination of the Jura Mountains coincides with the thinning out of these salt deposits [Jordan, 1994]. Thick-skinned tectonics in the Jura Mountains, only initiated in the Pliocene [Becker, 2000; Madritsch *et al.*, 2008], suggesting that the most significant foreland-directed shift of the orogen front, independent of preexisting upper crustal weaknesses, first started in the Pliocene.

3. Timing and Patterns of Exhumation in the Eastern, Central, and Western Alps

[10] The spatial evolution of exhumation through time is significantly different in the Western and central Alps, compared to the Eastern Alps. The Western and central Alps are characterized by the belt of External Crystalline Massifs (ECM), which entirely disappears in the Eastern Alps (Figure 1). These massifs are the expression of a late (15–2 Ma [Fügenschuh and Schmid, 2003]) exhumation of the lower (European) plate (Figure 2) in an external position, compared to the earlier, late Oligocene to early Miocene site of exhumation in the internal Western Alps and in the Lepontine dome (Figure 1). In the Western Alps this outward shift of the exhumation front took place in the Miocene, as shown by the progressive younging of zircon fission track ages (ZFT) from the axial zone (Periadriatic Fault) to the ECM (Figure 5a) [Fügenschuh and Schmid, 2003]. In the central Alps (Lepontine) an outward younging of the zircon fission track ages is not observed, because there the cooling pattern is affected by a young, high-temperature and late to posttectonic metamorphic event in the Lepontine [Wiederkehr *et al.*, 2008]. This event is inferred to have lasted until 20–18 Ma [Janots *et al.*, 2009], and therefore, it overprinted a cooling pattern that may eventually have been more similar to that of the Western Alps. However, the rates of cooling constrained for the temperature interval between 600°C and surface temperature (Figure 6) indicate that rapid cooling in the central Alps shifted northward, from the area bounding the retrowedge (Periadriatic Fault; Figure 1), to the area bounding the prowedge (Aar Massif; Figure 1).

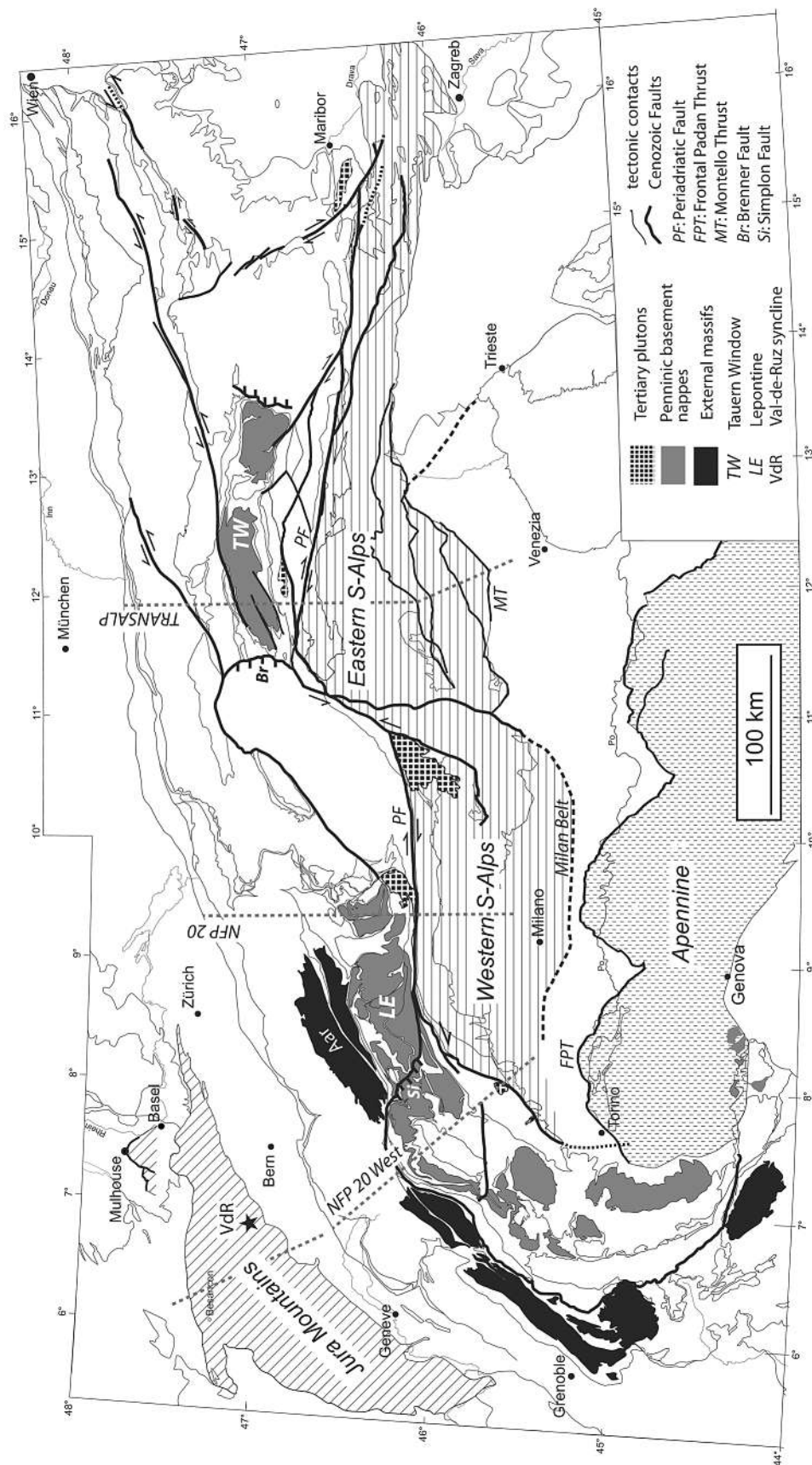


Figure 1. Simplified tectonic maps of the Alps. Note that the External Massif belt in the Western and central Alps, representing the external exhumation of the European plate, completely disappears in the Eastern Alps. Map modified after Schmid *et al.* [2004], Castellarin and Cantelli [2000], Piana [2000], and Nivière and Winter [2000].

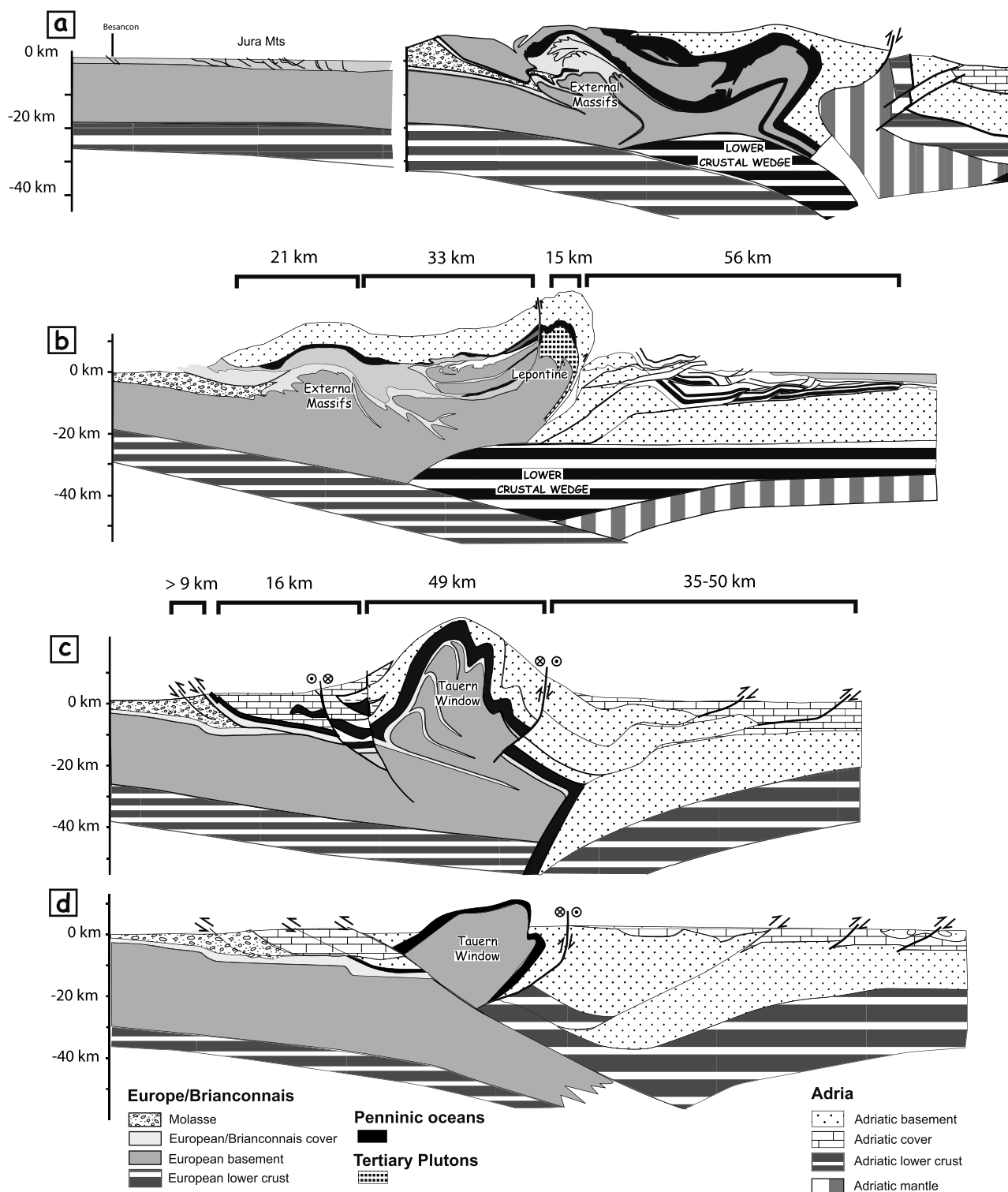


Figure 2. Lithospheric-scale cross sections of the Alps. (a) ECORS-CROP profile, modified after Schmid *et al.* [2004] and Burkhard and Sommaruga [1998]. (b) NFP 20 profile, modified after Schmid *et al.* [2004]. Numbers in Figures 2b and 2c indicate the amount of Neogene shortening, as discussed in the text. (c) TRANSALP profile, modified after Schmid *et al.* [2004]. (d) TRANSALP profile, modified after the TRANSALP Working Group [2002]. Note the occurrence of an orogen-scale lower crustal wedge in the central and Western Alps, terminating below the southernmost margin of the external massifs, and totally lacking in the eastern Alpine cross section.

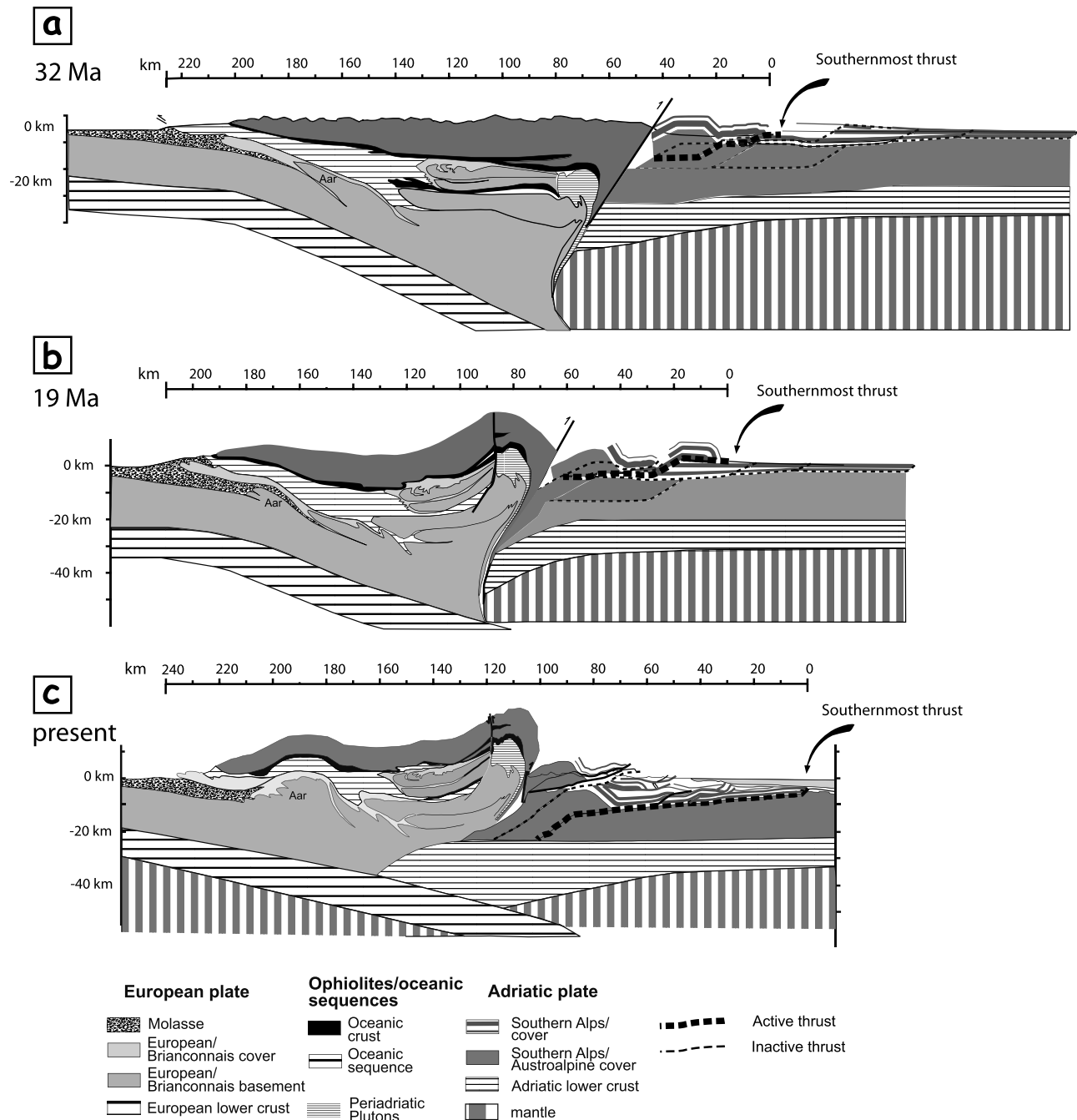


Figure 3. Cross sections showing the reconstructed width of the central Alps in the (a) late Oligocene, (b) middle Miocene, and (c) at present. The Southern Alps are redrawn after Schönborn [1992], and the northern part of the section is redrawn after Schmid *et al.* [1996]. Figure 3b is taken to represent the alpine width before the Burdigalian onset of thrusting in the Southern Alps. The southern deformation front in the Southern Alps at 19 Ma corresponds to the southernmost border of thrust system 2 of Schönborn [1992], inferred to be the first system to develop in the Burdigalian.

[11] The compiled apatite fission track (AFT) ages (Figure 5a) show that the youngest exhumation (<7 Ma) is located within an elongate, orogen-parallel belt that coincides with the external part of the ECMs of the Western and central Alps. AFT ages in the internal massifs are older, with

one exception at the western border of the Lepontine dome, probably due to young extensional deformation along the Simplon fault [e.g., Keller *et al.*, 2006] (Figure 5b).

[12] In contrast, in the Eastern Alps the area of enhanced exhumation remained localized within the axial zone of the

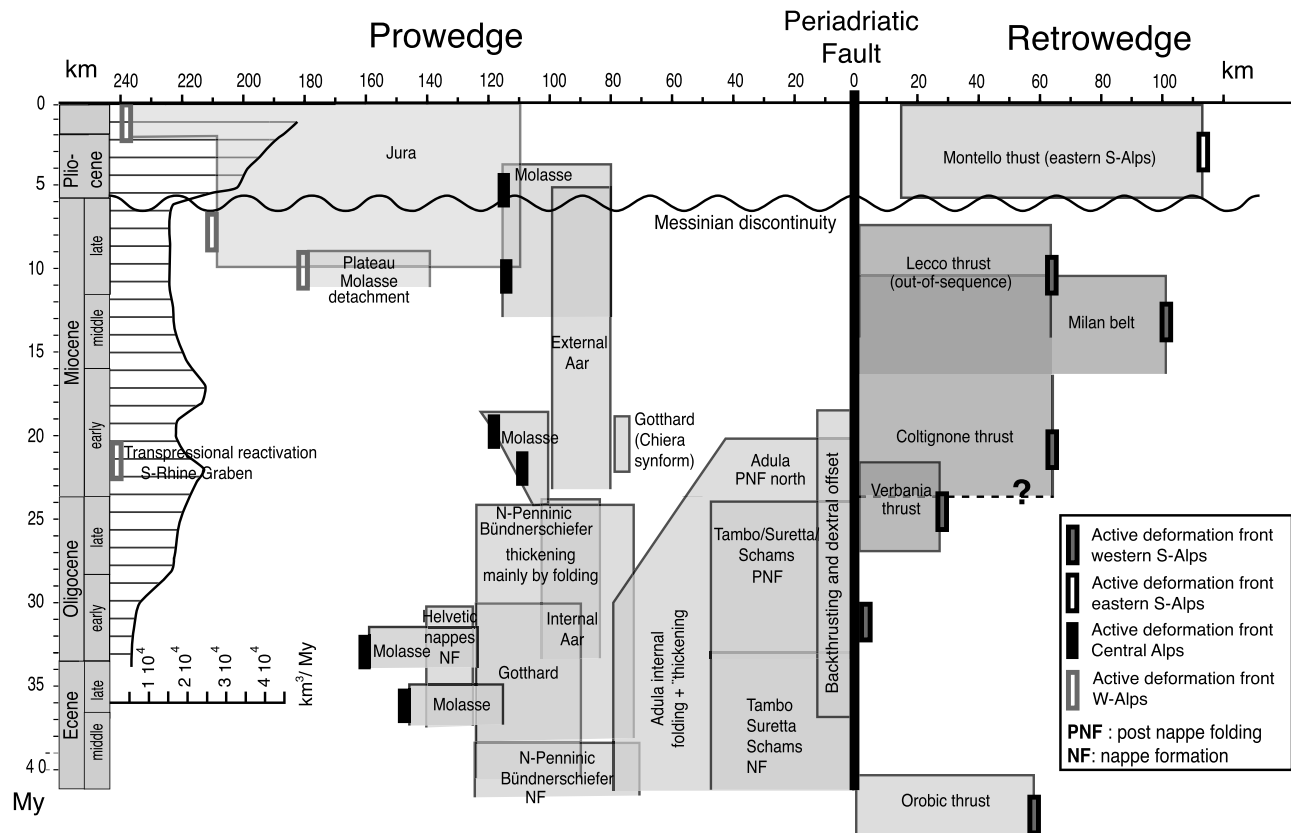


Figure 4. Temporal and spatial migration of the active deformation front of the Alps with respect to the present-day site of the Periadriatic Fault. Gray boxes indicate the time interval and the area affected by Tertiary tectonic phases. Vertical bars indicate the position of the most external part of thrusts in terms of their distance to the Periadriatic Fault at the time of activity of the thrust. This distance is calculated on the base of literature data from Becker [2000], Castellarin and Cantelli [2000], Nivière and Winter [2000], Pfiffner [1986], Pfiffner et al. [2002], Schmid et al. [1996], Schönborn [1992], and Schumacher et al. [1996]. For a discussion of the tectonic phases mentioned in the diagram the reader is referred to Schmid et al. [1996]. Horizontal bars and associated curve on the left side show the sediment budgets after Kuhlemann [2000] in km^3/Myr .

orogen (Tauern Window; Figure 1), as shown by the spatial coincidence of the youngest ages of both AFT and ZFT, forming the core of an elongate and concentric pattern of isocooling ages (Figures 5c and 5d). The FT ages indicate that this focused exhumation within the present-day Tauern Window lasted for over 20 Ma, from the Oligocene to the late Miocene (Figures 5a and 5b) [Luth and Willingshofer, 2008]. This area of enhanced exhumation also coincides with the hinge of the orogen-scale upright antiform of the Tauern Window (Figures 1 and 2c) [Lammerer et al., 2008; Rosenberg et al., 2007], which folds the European basement with the largest amplitude (approximately 30 km) observed in any of the cross sections of the Alps (Figure 2).

[13] The distinct style of exhumation in the central and Eastern Alps is even more pronounced when comparing the widths of the metamorphic belts exposed at the surface. In the Eastern Alps the width of this belt is less than half of that exposed in the central and Western Alps [Bousquet et al., 2008] (Figure 7), suggesting a much more focused type

of exhumation. These differences are consistent with the localized deformation into a single, large-amplitude antiform (the Tauern Window; Figure 2), instead of a more distributed, double-dome structure as in the central and Western Alps (Figures 1 and 2). The latter results from a two-stage evolution of postcollisional shortening, characterized by a first phase of backthrusting and nappe folding in the axial zone of the chain and a later phase of thrusting in an external position, leading to the formation of the ECMs.

[14] The FT ages (Figure 5) suggest that cooling, hence exhumation of the basement in the internal parts of the chain was coeval with the activity of the most external foreland-directed thrusts. In the Eastern Alps rapid exhumation occurred in the Tauern Window from the early to the late Miocene [Luth and Willingshofer, 2008], during activity of the Valsugana thrust, which formed the southern front of the orogen in that time interval. In the central and Western Alps, the orogen fronts of the Southern Alps were active during exhumation of the internal massifs, whereas the orogen

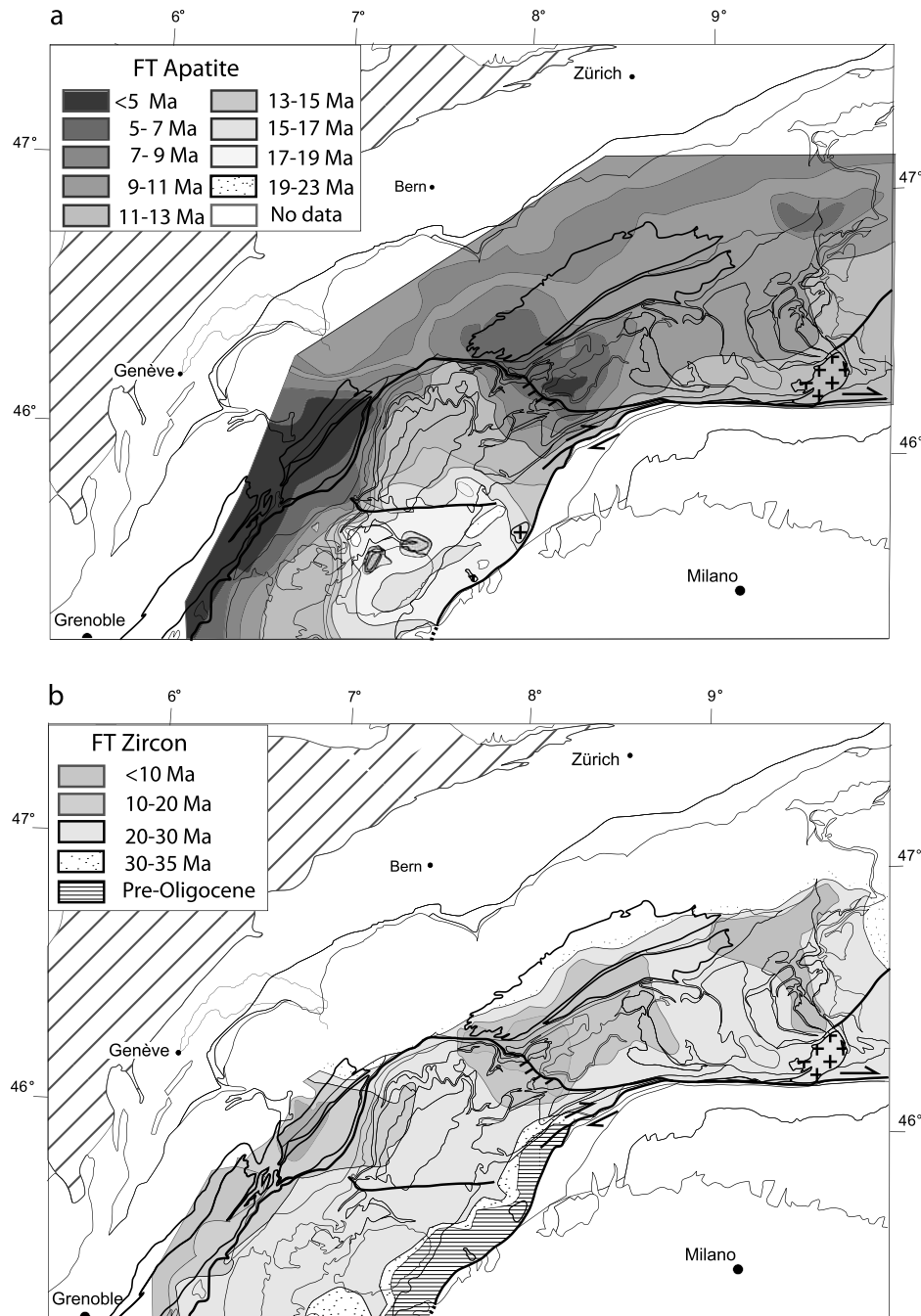


Figure 5. Compiled and contoured ages of fission tracks in zircons and apatites. (a) Apatite fission track ages in the central and Western Alps, redrawn after *Fügenschuh and Schmid* [2003], *Keller et al.* [2006], *Reinecker et al.* [2008], and *Vernon et al.* [2008]. (b) Zircon fission tracks in the central and Western Alps. Sources are the same as in Figure 5a. (c) Zircon fission track ages in the Eastern Alps. Compiled after *Dunkl et al.* [2003], *Fodor et al.* [2008], *Fügenschuh et al.* [1997], *Most* [2003], *Stöckhert et al.* [1999], *Viola et al.* [2001], and *Wölfler et al.* [2008]. Ages are normalized to a height of 1000 m on the base of exhumation rates published and/or calculated from the cited papers. (d) Apatite fission track ages in the Eastern Alps. Compiled after *Dunkl et al.* [2003], *Fodor et al.* [2008], *Foeken et al.* [2007], *Fügenschuh et al.* [1997], *Grundmann and Morteani* [1985], *Hejl* [1998], *Most* [2003], *Staufenberg* [1987], *Stöckhert et al.* [1999], *Viola et al.* [2001], and *Wölfler et al.* [2008]. Ages are normalized to a height of 1000 m on the base of exhumation rates published and/or calculated from the papers quoted above. * Color appears in back of the print issue.

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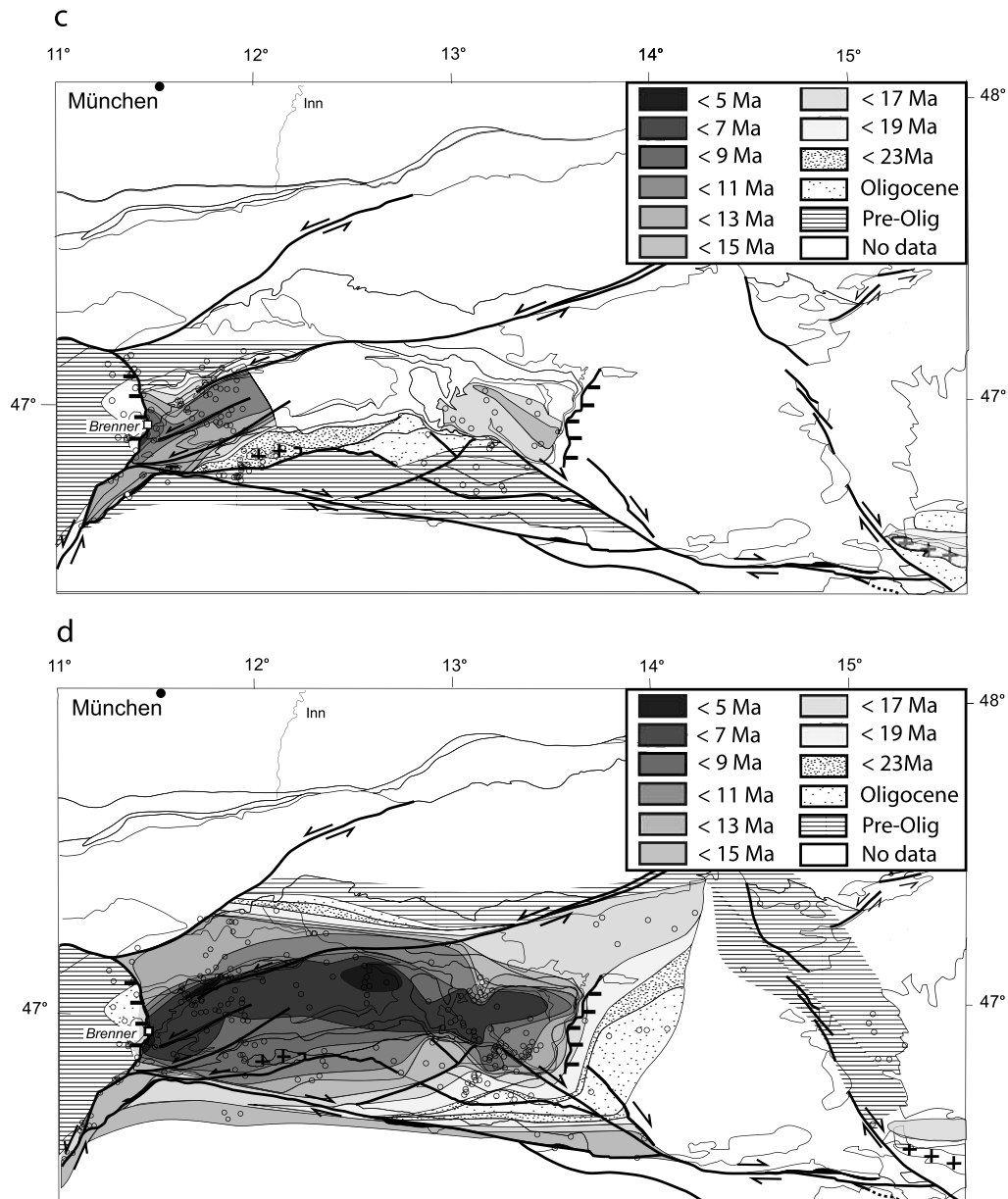


Figure 5. (continued). Color appears in back of the print issue.

front of the Jura Mountains was coeval with exhumation of the external Massifs.

4. Amount of Neogene Shortening Along the TRANSALP Section and Comparison With the NFP 20 Section

[15] The interpretation of the first-order differences in the temporal evolution of deformation and exhumation between the Eastern and the Western and central Alps, requires an estimate of the Neogene amount of shortening in these two portions of the orogen. If shortening is similar, it cannot be itself the cause for the different modes of lateral growth and exhumation. Below, we constrain Neogene N-S shortening in

the Eastern Alps, along the TRANSALP section (Figures 1, 2c, and 2d) based on literature data and own estimates. We then compare this amount of shortening to the one previously estimated in the central Alps [Schmid *et al.*, 1996]. We do not consider the western Alpine profiles for this comparison, because the geometry of the south alpine indenter is different in the Western Alps, resulting in different amounts of shortening perpendicular to the chain.

[16] In the northernmost part of the TRANSALP section, shortening is accommodated within the molasse sediments. Based on cross sections integrating seismic interpretations and surface geology in the Austrian Molasse basin [Berge and Veal, 2005, Figure 2] we can constrain at least 9 km of shortening (Figure 3c; note, however, that shortening may

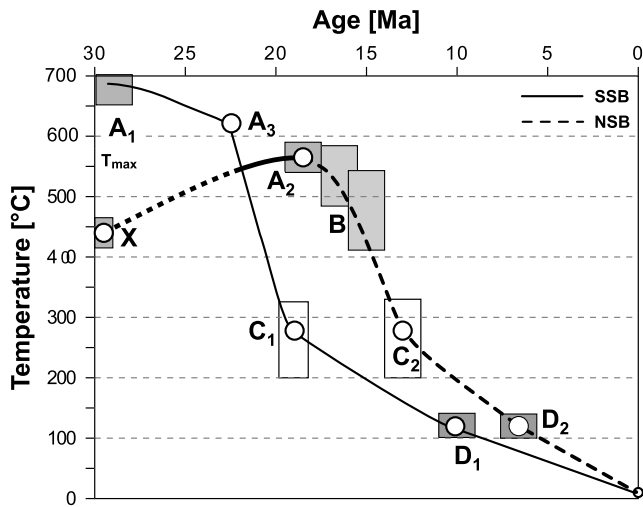


Figure 6. Cooling paths in the Southern Steep Belt and Northern Steep Belt of the central Alps, based on petrological and geochronological data of Allaz [2008], Janots *et al.* [2009], Berger *et al.* [2009], Hurford [1986], Michalski and Soom [1990], Rahn [2005], Wagner *et al.* [1977], and Rubatto *et al.* [2009]. A, U/Pb monazite and zircon ages; B, Ar/Ar mica ages; C, zircon FT; D, apatite FT; X, prograde allanite U/Pb age [Janots *et al.*, 2009]. NSB, Northern Steep Belt; SSB, Southern Steep Belt.

attain several tens of kilometers (H. Ortner, personal communication, 2009)). Retrodeformation of the northern Calcareous Alps along the TRANSALP section (Figure 1) indicates more than 55 km of post-Eocene N-S shortening [Behrmann and Tanner, 2006], but only 16 km are inferred to have taken place during the Neogene [Linzer *et al.*, 2002, Figure 10].

[17] Taking the TRANSALP cross section of Schmid *et al.* [2004] as a base (Figure 2c), 49 km of shortening in the Tauern Window can be assessed by simple line balancing of the folded boundary between Penninic and Austroalpine nappes. This boundary is folded by a crustal-scale, upright antiform, which is inferred to be Miocene in age, on the basis of combined structural [Rosenberg and Schneider, 2008] and geochronological data (Figure 5). The original length of the boundary surface between Austroalpine and Penninic units is unlikely to have remained constant during folding. A probable increase of this length during folding would imply that the shortening values inferred above bracket a maximum amount of shortening. An additional problem concerns the estimate of the lateral component of displacement, perpendicular to the cross section. Rock fabrics and their interpretation argue in favor of significant E-W extension [Behrmann, 1988; Selverstone, 1988], accommodating part of the shortening. If this is true, additional shortening is needed to retrodeform the Tauern antiform.

[18] In the southern Eastern Alps at least 35 km of middle Miocene to recent shortening are inferred by retrodeforming the Valsugana and the Montello faults (Figure 1) [Castellarin

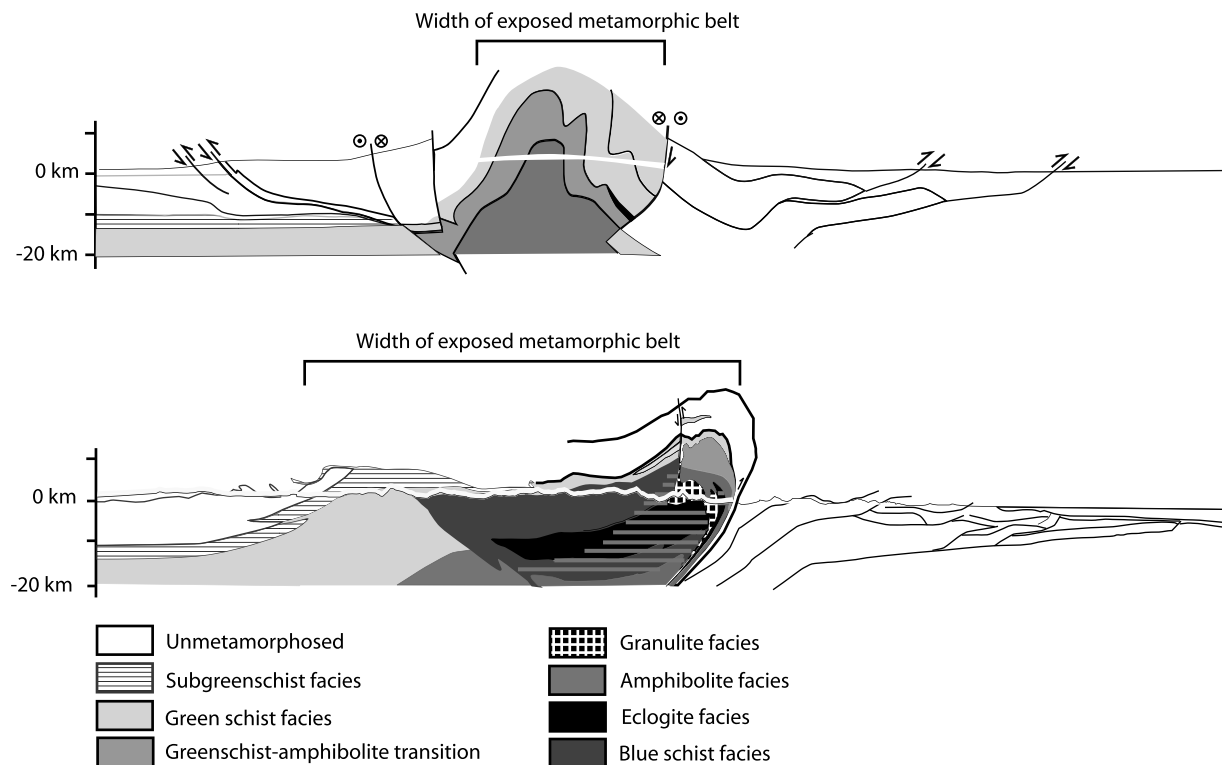


Figure 7. Cross sections of the central and the Eastern Alps showing the distribution of Tertiary metamorphic facies. Simplified after Bousquet *et al.* [2008]. Color appears in back of the print issue.

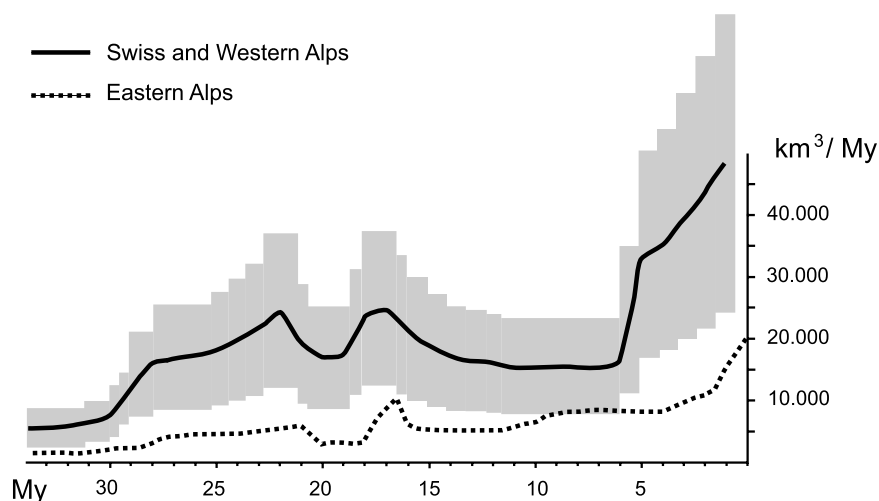


Figure 8. Sediment budgets in the foreland basins of the Alps, after *Kuhlemann et al.* [2002]. Light gray area is the estimated error referred to the Swiss and Western Alps.

and Cantelli, 2000]. However, balancing of cross sections from the same area, suggested at least 50 km of late Miocene to present shortening [Schönborn, 1999], consistent with previous estimates [Doglioni, 1987].

[19] Taken together, the estimates above point to a Neogene shortening value between 109 and 124 km. On the basis of the reconstruction of Schmid *et al.* [1996] the late Oligocene (32 Ma) to present amount of shortening along the NFP 20 traverse (central Alps) amounts to a total of 119 km and half of this shortening took place between 19 Ma and the present. Therefore, the total amount of Neogene shortening in the Eastern Alps and in the central Alps appears to be comparable.

5. Inferred Surface Controls on the Lateral Growth of the Orogen: A Critical Review

[20] The lateral migration of the deformation fronts of the Alps was suggested to be controlled by variations in the erosional efficiency, mainly attributed to climate changes [Schlunegger and Simpson, 2002] and to a minor extent to the exposure of basement rocks with higher resistance to erosion [Kühni and Pfiffner, 2001; Schlunegger, 1999; Schlunegger *et al.*, 2001; Schlunegger and Simpson, 2002]. Variations of erosional efficiency are inferred by quantifying sediment volumes per time interval that were deposited in the foreland basins [Schlunegger, 1999; Kuhlemann, 2000]. Climate changes were inferred on the basis of the floral paleontological record of the sediments [Schlunegger and Simpson, 2002]. The inferred temporal consistency between changes in the efficiency of erosion, the inferred climate change, and the inferred shift of the alpine deformation front, was used to suggest a climatic control on lateral growth [Schlunegger and Willett, 1999; Schlunegger and Simpson, 2002] and on lateral retreat [Willett *et al.*, 2006] of the Alps through time. Two such correlations have been claimed for the Cenozoic. A first one relates the outward growth of the

Alps into the Jura Mountains to the north and into the Southern Alps to the south, to a mid-Miocene reduction in the efficiency of erosion, caused by the transition toward a more arid climate [Schlunegger and Simpson, 2002]. A second one relates an increase of erosional efficiency following the Messinian salinity crisis [Kuhlemann, 2000] to back stepping of the deformation and exhumation fronts toward the axial part of the chain. This process was inferred to deactivate the external deformation fronts of the Jura Mountains and of the Southern Alps [Willett *et al.*, 2006]. We critically discuss the consistency of these two temporal correlations below.

5.1. Miocene Outward Growth of the Alps

[21] The southward propagation of the Alps into the Southern Alps was suggested to have occurred at 20–18 Ma [Schlunegger and Simpson, 2002], and the northward propagation into the Jura Mountains was suggested to have occurred at 14 Ma [Schlunegger and Simpson, 2002], but more likely at 10 Ma (see Becker [2000] for a review). Both tectonic events were inferred to result from the onset of a phase of reduced erosion rates [Schlunegger and Simpson, 2002]. However, the timing of these correlations is problematic because the variation of the sediment discharge rates [Kuhlemann, 2000] (Figure 8), which are used as a proxy for the erosion rates, lies within the error of estimate from the late Oligocene to the Messinian (Figure 8). In spite of these errors and in contrast to model predictions [Schlunegger and Willett, 1999] the inferred onset of lateral growth at 20–18 Ma coincides with a phase of increasing erosion rates, the highest ones ever attained during the Miocene (Figure 8). Finally, we emphasize that the timing of initiation of shortening in the Southern Alps is poorly defined, due to the lack of Miocene sediments [Schönborn, 1992; Schumacher *et al.*, 1996]. Schönborn [1992] and Schumacher *et al.* [1996] suggested that it is not older than Miocene, and possibly Burdigalian (20–16 Ma), but no evidence against an early

Miocene age (23–20 Ma) exists. A Burdigalian onset of thrusting is only based on the indirect and still debated overprinting relationships between the Insubric and Giudicarie faults [Schumacher *et al.*, 1996].

[22] The onset of deformation in the northwestern foreland of the Alps, leading to the formation of the Jura chain in the mid-Miocene, also does not coincide to a specific reduction in the erosional efficiency. According to Kuhlemann [2000], sedimentation rates in the central and Western Alps were relatively small between 15 and 5 Ma, and within the error of estimate they remained unchanged (Figure 8). Therefore, the initiation of shortening in the Jura Mountains took place in the middle of a 10 Ma long period characterized by low and constant erosion rates (Figure 8).

5.2. Messinian Back-Stepping of the Deformation Front

[23] The post-Messinian increase in the sediment budget is well defined (Figure 8) [Kuhlemann, 2000], but the inferred Messinian termination of tectonic activity in the foreland of the Alps [Willett *et al.*, 2006] is questionable. The claimed deactivation of folding and thrusting in the Jura Mountains before 3.4 Ma [Becker, 2000; Willett *et al.*, 2006] relies on the finding of ca. 3 Ma old micromammals in an undeformed karst fissure within the steep limb of an antiform [Bolliger *et al.*, 1993]. The tectonic significance of these paleontological findings is probably overinterpreted for the following reasons.

[24] 1. The 3 Ma old fauna fills a fissure of only 2 m length [Bolliger *et al.*, 1993, Figure 2]. Given the highly localized type of deformation in the Jura Mountains and the lack of thickness changes of the beds during deformation [e.g., Burkhard and Sommaruga, 1998], it would be an amazing coincidence if this small fissure had been internally deformed.

[25] 2. The latter fissure is located in the Val-de-Ruz syncline, which is in an internal (southern) position within the Jura chain (black star in Figure 1). Considering that the Jura Mountains probably form an in-sequence thrust and fold belt [Nivière and Winter, 2000], the termination of deformation can only be defined along the external folds and thrusts, not along the internal ones.

[26] 3. Irrespective of the 3 Ma old fissure mentioned above, there is good evidence for a continued formation of new thrusts and folds during the Pliocene and Pleistocene [Jouanne *et al.*, 1998; Nivière and Winter, 2000; Giamboni *et al.*, 2004], which shifted the deformation front approximately 30 km farther north, directly south of Mulhouse [Nivière and Winter, 2000] (Figure 1), and ~20 km farther west in the Châinées Subalpines [Lickorish and Ford, 1998]. Although the interpretation of GPS data only indicates small amounts of convergence [Walpersdorf *et al.*, 2006], neotectonic structures and seismicity pointing to recent shortening do occur [Philippe *et al.*, 1996; Thouvenot *et al.*, 1998; Becker, 2000; Lacombe and Mouthereau, 2002; Giamboni *et al.*, 2004].

[27] 4. Seismic interpretations point to a change from thin-skinned to thick-skinned tectonics in the Jura Mountains after 3 Ma [Becker, 2000; Lacombe and Mouthereau,

2002; Ustaszewski and Schmid, 2007], not to a termination of tectonic activity. Therefore, we conclude that at no time did the deformation front step back from the Jura Mountains toward a more internal position into the Alpine chain.

[28] The Messinian deactivation of the south Alpine thrusts [Pieri and Groppi, 1981; Schönborn, 1992] was inferred to mark the transition from southward directed growth of the Southern Alps to northward directed retreat, toward the orogen interior [Willett *et al.*, 2006]. However, several observations suggest that the active deformation front of the Southern Alps continued to migrate southward after the Messinian. In the eastern Southern Alps (Figure 1) N-S shortening is well documented from the Miocene, through the Pliocene [Castellarin and Vai, 1981; Castellarin and Cantelli, 2000], and to the present [Benedetti *et al.*, 2000], forming an in-sequence thrust-and-fold belt, which is translated by more than 20 km into the hinterland after the Messinian (Montello thrust in Figure 1 [Castellarin and Cantelli, 2000]). Even in the western Southern Alps, N-S shortening did not step back into the core of the orogen, but migrated to an even more external position, namely, within the Padan Front Thrust [Piana, 2000] (Figure 1). This shift of the deformation front into the Apennines is due to a major plate rearrangement [Laubscher, 2001]. As illustrated in map view (Figure 1), the Apennines are very close to the western Southern Alps, but their distance to the Alps progressively increases eastward. Therefore, the observed post-Messinian shift of N-S shortening from the Alps to the Apennines in the west, and the prolonged shortening of the Southern Alps in post-Messinian time farther east, are not surprising and should be regarded as the result of continuous, post-Messinian incorporation of the southern foreland into the orogen.

6. Discussion

6.1. Deep-Seated, Structural Controls on the Lateral Growth and Exhumation of the Alpine Orogen

[29] The interpretation of seismic sections shows some significant differences in the lower crustal structure of the Western and central Alps, compared to the Eastern Alps. [e.g., Kissling *et al.*, 2006]. All cross sections of the central and Western Alps (Figure 2, and additional sections in the works by Schmid *et al.* [2004] and Kissling *et al.* [2006]) are characterized by a lower crustal wedge, defined by higher seismic velocities [Schmid *et al.*, 1996; Schmid and Kissling, 2000; Kissling *et al.*, 2006] (Figure 2), interpreted as overthrust, hence doubled lower crust, accommodating up to 60 km of shortening. The northern termination of these wedges coincides with the projection of frontal thrusts of the ECMs at depth (Figure 2). In the Western Alps the lower crustal wedge consists of European crust, in the central Alps of Adriatic crust (Figures 2a and 2b), but their geometries and structural positions are similar [Schmid *et al.*, 2004, Figure 3]. We therefore expect these wedges to cause analogous mechanical effects on the lower plate of the orogen. In the Eastern Alps (see Figure 2c and Schmid *et al.* [2004] for additional cross sections), the deep structure of the orogen is different. No lower crustal wedge (Figure 2c)

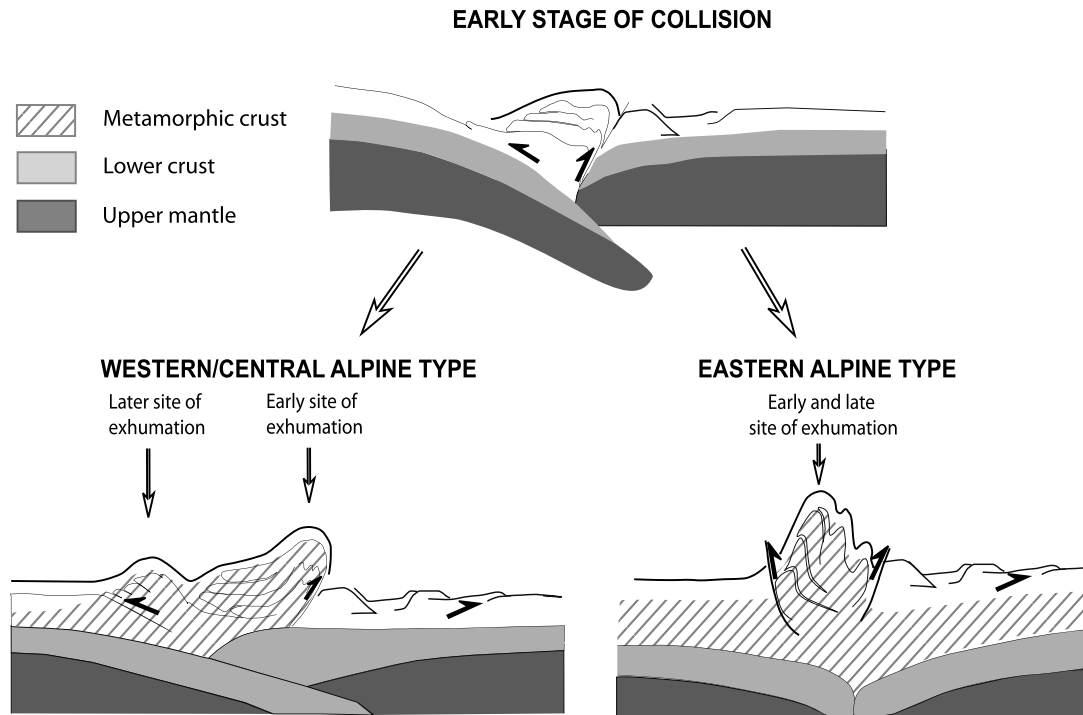


Figure 9. Schematic cross sections illustrating the differences in the style of deformation and exhumation of the Eastern Alps and the central Alps as a function of the difference in the structure of the lower crust. Hatched areas show the extent of the metamorphic belts.

[Schmid *et al.*, 2004; Bleibinhaus and Gebrande, 2006; Kissling *et al.*, 2006] is observed to override the lower crust of the lower plate of the orogen. Alternative interpretations do show an incipient lower crustal Adriatic wedge (Figure 2d) [TRANSALP Working Group, 2002; Lüschen *et al.*, 2004], the geometry of which, however, significantly differs from that of the lower crustal wedges of the Western Alps. First, the inferred Adriatic wedge in the Eastern Alps terminates at the southern boundary of the Tauern Window [Lüschen *et al.*, 2004], hence in a much more internal position than in the Western Alps. Second, the inferred basal detachment of the incipient lower crustal wedge is much steeper than in the Western Alps, resulting in the overthrusting of the upper instead of the lower European crust (Figure 2d). Whatever interpretation is favored, no significant doubling of the lower crust and no significant northward displacement of the lower crust can be inferred in the Eastern Alps.

[30] Summarizing the observations above, two major differences characterize the orogen-scale cross sections and the exhumation of the Western and central Alps and of the Eastern Alps [Schmid *et al.*, 2004] (Figure 2). First, in the central and Western Alps, shortening of the European basement is distributed both in the axial zone (Leptontine dome; Figure 1) and in the ECMs (Figures 1 and 2). This distributed type of deformation and exhumation goes together with lower crustal thrusting, displacing the deformation front of the European basement from the Periadriatic Fault (Figure 1) to the ECMs. In contrast, in the Eastern Alps, where northward thrusting of a lower crustal wedge

is not observed, or only of subordinate importance, the bulk shortening of the European basement concentrated in the axial zone of the orogen, leading to the high-amplitude, upright folds of the Tauern Window and to a long-term localization of exhumation in one and the same area.

[31] These differences in the lower crustal geometry correlate with the differences in the patterns of surface deformation and cooling. The northward displacement of up to 60 km inferred for the lower crustal wedges in the central and Eastern Alps explains the Miocene shift of the exhumation and deformation front toward the northern foreland of the orogen. This leads to a broader exposure of metamorphic rocks (Figure 7) [Bousquet *et al.*, 2008]. In contrast, the absence of a northward directed lower crustal wedge in the Eastern Alps (Figures 2 and 9) allowed for a more stationary type of deformation and exhumation in the immediate vicinity of the retrowedge.

[32] Alternatively deep-seated rheological differences may be advocated to explain a focused mode of deformation and exhumation in the Eastern Alps in contrast to a more distributed one in the central Alps. Strong brittle-ductile coupling, i.e., higher viscosity of the ductile crust, induces a more distributed type of deformation [Schueller *et al.*, 2005]. However, on the basis of metamorphic investigations there is no reason to assume higher temperatures, and hence, lower viscosity of the Miocene ductile crust in the Eastern Alps compared to the central Alps.

[33] Irrespective of the absolute rates of erosion and their changes through time, the reconstructed cross section of the Eastern Alps along the TRANSALP seismic profile

(Figure 2c) testifies that erosion was sufficiently efficient to remove the material from the hinge of a crustal-scale antiform, hence allowing the European basement to cumulatively thicken by a factor of three (Figure 2c) throughout the Cenozoic time. We emphasize that the occurrence of low-angle normal faults in this area [Behrmann, 1988; Selverstone, 1988] does not modify the latter interpretation. Irrespective of a component of orogen-parallel extension, the antiform of the western Tauern Window (Figure 2c) forms the thickest stack of European basement observed in the Alps, and the most convincing example of enhanced exhumation in one and the same place throughout the Neogene (Figures 5c and 5d). Retrodeformation of the orogen-parallel component of extension would result in an even more dramatic thickening of this crust.

6.2. Did Climatic/Erosional Changes Control the Lateral Growth of the Alps?

[34] As discussed above, the expected temporal correlations between changes in erosional efficiency and lateral shifts of the deformation fronts cannot be assessed in the Alps (Figure 4). The most dramatic increase of sediment discharge rates is the post-Messinian one (Figure 8) and the most dramatic increase of width of the Alps corresponds to the formation of the Jura Mountains (Figure 1) at 10 Ma. Hence, these two events are the most critical ones to assess the relationship between erosional efficiency and lateral growth of the orogen. The initiation of the Jura Mountains does not correspond to a specific change in the sediment discharge rates. In contrast, this phase of lateral growth initiated in the middle of a long interval of low, but constant sediment discharge rates (Figure 8) [Kuhlemann, 2000], which started at least 5 Ma before the formation of the Jura Mountains. Therefore, there is no specific temporal link between these processes. On the other hand, there is also a lack of evidence for a reduction of the width of the deforming Alpine Chain after the Messinian. Deformation continued to migrate outward, both to the north and to the south in spite of a dramatic increase of sediment discharge after 4 Ma [Kuhlemann, 2000] (Figures 4 and 8). The southern deformation front migrated from the alpine Milan Belt into the Apenninic Padan Front Thrust [Piana, 2000] (Figure 1) in the western Southern Alps and to the Montello thrust in the eastern Southern Alps (Figure 1) [Benedetti *et al.*, 2000]. The northern front migrated from the Jura Mountains into the Rhine and Bresse grabens [Nivière and Winter, 2000; Giamboni *et al.*, 2004; Madritsch *et al.*, 2008]. On the base of seismic interpretation [Becker, 2000; Lacombe and Mouthereau, 2002] and tectonic and geomorphic interpretations [Madritsch *et al.*, 2008] this shift was associated to a transition from thin-skinned to thick-skinned tectonics. Therefore, the most significant shift of the deep-seated, thick-skinned site of deformation took place in the Pliocene [Madritsch *et al.*, 2008], displacing the deep-seated Alpine front by more than 100 km toward the foreland, during a dramatic increase of erosional efficiency.

[35] The lower middle Miocene, which is inferred to mark the onset of decreasing erosional efficiency (Figure 8) [Kuhlemann, 2000] does coincide to a phase of increasing

width of the orogen (Figure 4), but this phase started already in the late Oligocene, as the erosional efficiency of the orogen was about to attain a maximum (Figures 4 and 8). In addition, the South Alpine deformation front stepped back into the Lecco out-of-sequence thrust in the late Miocene, during a period of inferred constant and low erosional efficiency (Figures 4 and 8). These relationships between the inferred shifts of the orogen front and the erosional efficiency contradict the expected control exerted by erosion on the width of orogens [e.g., Beaumont *et al.*, 1992], suggesting that other processes must have exerted the prime control the site of the active front.

6.3. Comparison Between Erosional Efficiency and Exhumation in the Eastern and Central Alps

[36] The first-order trend of the sediment discharge rates of the Western and central Alps and of the Eastern Alps are similar (Figure 8) [Kuhlemann *et al.*, 2002], characterized by increasing rates from 35 Ma to 17 Ma [Kuhlemann, 2000] (Figure 8). This increase is followed by a decrease from 17 to 4–6 Ma, i.e., until the Messinian, which marks the initiation of a new and dramatic increase of sediment discharge rates until the present.

[37] Given the similar trend in the sediment budgets of the Western, central, and Eastern Alps, a similar and coeval trend in the lateral shift of the exhumation fronts of these parts of the Alpine chain could be expected. However, as discussed above the modes of exhumation of the Eastern and central/Western Alps are different, suggesting that erosion was not the controlling factor. In the Eastern Alps the axial zone of the chain (Tauern Window) remains the prime site of shortening and exhumation from the late Oligocene to the present (Figure 5). The youngest apatite ages occur along an elongate area corresponding to the long axis of the Tauern Window (Figures 1, 5c, and 5d) and this area is identical with the one defined by the youngest zircon ages. This indicates that the site of enhanced exhumation in the Eastern Alps remained nearly unchanged throughout the Miocene (Figure 2).

[38] In contrast, in the Western/central Alps the youngest FT ages in apatite (2 to 5 Ma, but mostly around 5 Ma) are located along the northern margin of the external massifs and immediately north of them (Figure 5a), whereas the axial zone of the orogen is characterized by older ages clustering around 8 to 9 Ma in the Lepontine and between 23 and 15 Ma in the internal Western Alps (Figure 5a). The only exception to this trend is observed in the footwall of the Simplon normal fault and at the eastern boundary of the Lepontine (Figures 1 and 5b), where young ages occur, probably due to late Miocene–Pliocene extensional activity. The shift of the exhumation front from the Lepontine to the northern margin of the external massifs (Figure 5b) leads to a much wider zone of exposure of Tertiary metamorphic rocks (Figure 7) [Bousquet *et al.*, 2008] compared to the Eastern Alps.

7. Conclusions

[39] The migration of the deformation fronts into the foreland of the Alps is not temporally correlated to specific

changes in the sediment discharge rates of the orogen. On the other hand, marked changes of sediment budgets in the Perialpine basins are not correlated to specific growth or retreat phases of the orogen fronts, suggesting that erosional efficiency did not play a controlling role in initiating phases of lateral growth and lateral retreat of the orogen. The lack of these temporal/spatial correlations in the Tertiary Alpine Chain is in contrast to the results of numerical models showing a strong control of erosion on the evolving orogen width [Willett, 1999; Beaumont *et al.*, 2000]. Different factors may explain this discrepancy. One possibility may be that an existent correlation between changes of erosional efficiency and changes of width of the Alps are masked by the still insufficient temporal constraints on the timing of lateral growth, especially in the western Southern Alps, and the poor temporal and volumetric constraints on the sediment budgets of the Perialpine basins. Alternatively, deep-seated processes had a stronger and controlling effect on the width of the orogen, compared to surface processes. Because there is no geologic evidence supporting lower viscosity of the ductile crust in the Eastern Alps, compared to the central Alps the more likely cause for the different styles of exhumation resides in the lower crustal configuration. The occurrence of lower crustal wedges overthrusting the lower plate of the orogen in all Alpine sections containing the external crystalline massifs, and the more distributed type of exhumation in these sections compared to the focused, long-term localized exhumation in sections lacking a lower crustal wedge, point to a causal relationship between deep crustal tectonics and exhumation style. The relative northward displacement of lower crustal wedges in the Western and central Alps probably caused the outward shift of the deformation and exhumation

fronts, whereas the absence of such a wedge in the Eastern Alps resulted in a more stationary, localized type of deformation and exhumation. The spatial evolution of the site of maximum exhumation may be different from that of the deformation fronts, but erosional changes are expected to affect the shifts of the sites of maximum shortening, which do coincide with those of maximum exhumation in the collisional history of the Alps. Therefore, the outward migration of exhumation in the central and Western Alps as opposed to the stationary exhumation of the Eastern Alps contradict the idea of a primary climatic control on the growth of the Alpine chain. Climatic changes, and the associated variations in erosional efficiency would act on a scale at least as large as that of the Alpine chain, inducing similar erosional and tectonic responses in the entire orogen. No climatic barrier between the Eastern and the central Alps is known to exist in the present, neither to have existed in the past. The relative changes in the sediment discharge rates in the Eastern and Western/central Alps are nearly coeval, but the timing, the mode of exhumation and the propagation of the deformation fronts are different in these two parts of the orogen. Therefore, the effects of climatic and erosional changes, which certainly influence the width of orogens, may not have been sufficiently intense to cause lateral growth and/or retreat of the Alps. Changes in the deep structure of the orogen appear to have had the prime control on the lateral migration of the exhumation fronts.

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References

- Allaz, J. (2008), Metamorphic evolution in the northern central Alps: Linking ^{39}Ar - ^{40}Ar dating with thermobarometry, 214 pp., Ph.D. thesis, Univ. of Bern, Bern.
- Avouac, J. P., and E. B. Burov (1996), Erosion as a driving mechanism of intracontinental mountain growth, *J. Geophys. Res.*, **101**, 17,747–17,769, doi:10.1029/96JB01344.
- Beaumont, C., P. Fullsack, and J. Hamilton (1992), Erosional control of active compressional orogens, in *Thrust Tectonics*, edited by K. R. McClay, pp. 19–31, Chapman and Hall, New York.
- Beaumont, C., H. Kooi, and S. D. Willett (2000), Progress in coupled tectonic-surface process models with application to rifted margins and collisional orogens, in *Geomorphology and Global Tectonics*, edited by M. A. Summerfield, pp. 29–55, John Wiley and Sons, Ltd., S.D.
- Becker, A. (2000), The Jura Mountains—An active foreland fold-and-thrust belt?, *Tectonophysics*, **321**, 381–406, doi:10.1016/S0040-1951(00)00089-5.
- Behrmann, J. H. (1988), Crustal-scale extension in a convergent orogen: The Sterzing-Steinach mylonite zone in the Eastern Alps, *Geodin. Acta*, **2**, 63–73.
- Behrmann, J., and D. Tanner (2006), Structural synthesis of the northern Calcareous Alps, TRANSALP segment, *Tectonophysics*, **414**, 225–240, doi:10.1016/j.tecto.2005.10.018.
- Benedetti, L., P. Tapponnier, G. C. P. King, B. Meyer, and I. Manighetti (2000), Growth folding and active thrusting in the Montello region, Veneto, northern Italy, *J. Geophys. Res.*, **105**, 739–766, doi:10.1029/1999JB900222.
- Berge, T. B., and S. L. Veal (2005), Structure of the Alpine foreland, *Tectonics*, **24**, TC5011, doi:10.1029/2003TC001588.
- Berger, A., and R. Bousquet (2008), Subduction-related metamorphism in the Alps: Review of isotopic ages based on petrology and their geodynamic consequences, in *Tectonic Aspects of the Alpine-Dinaride-Carpathian System*, edited by S. Siegesmund, B. Fügenschuh, and N. Froitzheim, *Geol. Soc. Spec. Publ.*, **298**, 117–144, doi:10.1144/SP298.7.
- Berger, A., C. L. Rosenberg, and U. Schaltegger (2009), Stability and isotopic dating of monazite and allanite in partially molten rocks: Examples from the central Alps, *Swiss J. Geosci.*, **102**, 15–29, doi:10.1007/s00015-009-1310-8.
- Bernet, M., M. Zattin, J. I. Garver, M. T. Brandon, and J. A. Vance (2001), Steady-state exhumation of the European Alps, *Geology*, **29**, 35–38, doi:10.1130/0091-7613(2001)029<0035:SSEOTE>2.0.CO;2.
- Bleibinhaus, F., and H. Gebrande (2006), Crustal structure of the Eastern Alps along the TRANSALP profile from wide-angle seismic tomography, *Tectonophysics*, **414**, 51–69, doi:10.1016/j.tecto.2005.10.028.
- Bolliger, T., B. Engesser, and M. Weidmann (1993), Première découverte des mammifères pliocènes dans le Jura neuchâtelois, *Eclogae Geol. Helv.*, **86**, 1031–1068.
- Bousquet, R., R. Oberhänsli, B. Goffé, M. Wiederkehr, F. Koller, S. M. Schmid, R. Schuster, M. Engi, A. Berger, and G. Martinotti (2008), Metamorphism of metasediments at the scale of an orogen: A key to the Tertiary geodynamic evolution of the Alps, in *Tectonic Aspects of the Alpine-Dinaride-Carpathian System*, edited by S. Siegesmund, B. Fügenschuh, and N. Froitzheim, *Geol. Soc. Spec. Publ.*, **298**, 393–411, doi:10.1144/SP298.18.
- Burkhard, M., and A. Sommaruga (1998), Evolution of the western Swiss Molasse basin: Structural relations with the Alps and the Jura belt, in *Cenozoic Foreland Basins of Western Europe*, edited by A. Mascle *et al.*, *Geol. Soc. Spec. Publ.*, **134**, 198–279, doi:10.1144/GSL.SP.1998.134.01.13.
- Castellarin, A., and L. Cantelli (2000), Neo-Alpine evolution of the southern Eastern Alps, *J. Geodyn.*, **30**, 251–274, doi:10.1016/S0264-3707(99)00036-8.
- Castellarin, A., and G. B. Vai (1981), Importance of Hercynian tectonics within the framework of the southern Alps, *J. Struct. Geol.*, **3**, 477–486, doi:10.1016/0191-8141(81)90047-X.

- Cederbom, C. E., H. D. Sinclair, F. Schlunegger, and M. K. Rahn (2004), Climate-induced rebound and exhumation of the European Alps, *Geology*, **32**, 709–712, doi:10.1130/G20491.1.
- Dahlen, F. A. (1984), Noncohesive critical Coulomb wedges: An exact solution, *J. Geophys. Res.*, **89**, 10,125–10,133, doi:10.1029/JB089iB12p10125.
- Doglioni, C. (1987), Tectonics of the Dolomites (southern Alps, northern Italy), *J. Struct. Geol.*, **9**(2), 181–193, doi:10.1016/0191-8141(87)90024-1.
- Doglioni, C., E. Carminati, M. Cuffaro, and D. Scrocca (2007), Subduction kinematics and dynamic constraints, *Earth Sci. Rev.*, **83**, 125–175, doi:10.1016/j.earscirev.2007.04.001.
- Dunkl, I., W. Frisch, and G. Grundmann (2003), Zircon fission track thermochronology of the southeastern part of the Tauern Window and the adjacent Austroalpine margin, Eastern Alps, *Eclogae Geol. Helv.*, **96**, 209–217.
- Fodor, L. I., et al. (2008), Miocene emplacement and rapid cooling of the Pohorje pluton at the Alpine-Pannonian-Dinaric junction, Slovenia, *Swiss J. Geosci.*, **101**, 255–271, doi:10.1007/s00015-008-1286-9.
- Foeken, J. P. T., C. Persano, F. M. Stuart, and M. ter Voorde (2007), Role of topography in isotherm perturbation: Apatite (U-Th)/He and fission track results from the Malta tunnel, Tauern Window, Austria, *Tectonics*, **26**, TC3006, doi:10.1029/2006TC002049.
- Fügenshuh, B., and S. M. Schmid (2003), Late stages of deformation and exhumation of an orogen constrained by fission-track data: A case study in the Western Alps, *Geol. Soc. Am. Bull.*, **115**, 1425–1440, doi:10.1130/B25092.1.
- Fügenshuh, B., D. Seward, and N. S. Mancktelow (1997), Exhumation in a convergent orogen: The western Tauern Window, *Terra Nova*, **9**, 213–217, doi:10.1046/j.1365-3121.1997.d01-33.x.
- Garzanti, E., and M. G. Malusà (2008), The Oligocene Alps: Domal unroofing and drainage development during early orogenic growth, *Earth Planet. Sci. Lett.*, **268**, 487–500, doi:10.1016/j.epsl.2008.01.039.
- Giamboni, M., K. Ustaszewski, S. M. Schmid, M. Schumacher, and A. Wetzel (2004), Plio-Pleistocene deformation in the southern Upper Rhine Graben area: Geological and geomorphological evidence for on-going transpressive reactivation of Paleozoic and Paleogene faults, *Int. J. Earth Sci.*, **93**, 207–223, doi:10.1007/s00531-003-0375-2.
- Grundmann, G., and G. Morteani (1985), The young uplift and thermal history of the central Eastern Alps (Austria/Italy), evidence from apatite fission track ages, *Jahrb. Geol. Bundesanst.*, **128**, 197–216.
- Handy, M., and R. Oberhänsli (2004), Age map of the metamorphic structure of the Alps—Tectonic interpretation and outstanding problems, in *Explanatory Notes to the Map: Metamorphic Structure of the Alps*, edited by R. Oberhänsli, *Mitt. Oesterr. Geol. Ges.*, **149**, 97–121.
- Hejl, E. (1998), Über die kanozoische Abkühlung und Denudation der Zentralalpen östlich der hohen Tauern-eine Apatit Spaltspuranalyse, *Mitt. Oesterr. Geol. Ges.*, **89**, 179–199.
- Hurford, J. (1986), Cooling and uplift patterns in the Lepontine Alps and an age of movement on the Insubric Fault Line, south central Switzerland, *Contrib. Mineral. Petrol.*, **92**, 413–429, doi:10.1007/BF00374424.
- Janots, E., M. Engi, D. Rubatto, A. Berger, C. Gregory, and M. Rahn (2009), Metamorphic rates in collisional orogeny from in situ allanite and monazite dating, *Geology*, **37**, 11–14, doi:10.1130/G25192A.1.
- Jordan, P. (1994), Evaporite als Abscherhorizonte, *Beitr. Geol. Karte Schweiz, Lieferung*, **164**, 79.
- Jouanne, F., N. Genaudeau, G. Ménard, and X. Darmendrail (1998), Estimating present-day displacement fields and tectonic deformation in active mountain belts: An example from the Chartreuse Massif and the southern Jura Mountains, Western Alps, *Tectonophysics*, **296**, 403–419, doi:10.1016/S0040-1951(98)00156-5.
- Keller, L. M., B. Fügenshuh, M. Hess, B. Schneider, and S. M. Schmid (2006), Simplon fault zone in the western and central Alps: Mechanism of Neogene faulting and folding revisited, *Geology*, **34**, 317–320, doi:10.1130/G22256.1.
- Kissling, E., S. M. Schmid, R. Lippitsch, J. Ansoerge, and B. Fügenshuh (2006), Lithosphere structure and tectonic evolution of the Alpine arc: New evidence from high-resolution teleseismic tomography, in *European Lithosphere Dynamics*, edited by D. G. Gee and R. A. Stephenson, *Geol. Soc. Mem.*, **32**, 129–145, doi:10.1144/GSL.MEM.2006.032.01.08.
- Konstantinovskaia, E., and J. Malavieille (2005), Erosion and exhumation in accretionary orogens: Experimental and geological approaches, *Geochim. Geophys. Geosyst.*, **6**, Q02006, doi:10.1029/2004GC000794.
- Kuhlemann, J. (2000), Post-collisional sediment budget of circum-Alpine basins (central Europe), *Mem. Sci. Geol. Padova*, **52**, 1–91.
- Kuhlemann, J., W. Frisch, B. Székely, I. Dunkl, and M. Kázmér (2002), Post-collisional sediment budget history of the Alps: Tectonic versus climatic control, *Int. J. Earth Sci.*, **91**, 818–837, doi:10.1007/s00531-002-0266-y.
- Kuhlemann, J., I. Dunkl, A. Brügler, C. Spiegel, and W. Frisch (2006), From source terrains of the Eastern Alps to the Molasse Basin: Detrital record of non-steady-state exhumation, *Tectonophysics*, **413**, 301–316, doi:10.1016/j.tecto.2005.11.007.
- Kühni, A., and O. A. Pfiffner (2001), The relief of the Swiss Alps and adjacent areas and its relation to lithology and structure: Topographic analysis from a 250-m DEM, *Geomorphology*, **41**, 285–307, doi:10.1016/S0169-555X(01)00060-5.
- Lacombe, O., and F. Mouthereau (2002), Basement-involved shortening and deep detachment tectonics in forelands of orogens: Insights from recent collision belts (Taiwan, Western Alps, Pyrenees), *Tectonics*, **21**(4), 1030, doi:10.1029/2001TC901018.
- Lammerer, B., H. Gebrande, E. Lüschen, and P. Veselá (2008), A crustal-scale cross-section through the Tauern Window (Eastern Alps) from geophysical and geological data, in *Tectonic Aspects of the Alpine-Dinaride-Carpathian System*, edited by S. Siegesmund, B. Fügenshuh, and N. Froitzheim, *Geol. Soc. Spec. Publ.*, **298**, 219–229, doi:10.1144/SP298.11.
- Laubscher, H. (1961), Die Fernschubhypothese der Jurafaltung, *Eclogae Geol. Helv.*, **54**, 222–282.
- Laubscher, H. P. (2001), Plate interactions at the southern end of the Rhine graben, *Tectonophysics*, **343**, 1–19, doi:10.1016/S0040-1951(01)00193-7.
- Lickorish, W. H., and M. Ford (1998), Sequential restoration of the external Alpine Digne thrust system, SE France, constrained by kinematic data and synorogenic sediments, in *Cenozoic Foreland Basin of Western Europe*, edited by A. Mascle et al., *Geol. Soc. Spec. Publ.*, **134**, 189–211, doi:10.1144/GSL.SP.1998.134.01.09.
- Linzer, H.-G., K. Decker, H. Peresson, R. Dell'Mour, and W. Frisch (2002), Balancing orogenic float of the Eastern Alps, *Tectonophysics*, **354**, 211–237, doi:10.1016/S0040-1951(02)00337-2.
- Lüschen, E., B. Lammerer, H. Gebrande, K. Millahn, R. Nicolich, and the TRANSALP Working Group (2004), Orogenic structure of the Eastern Alps, Europe, from TRANSALP deep seismic reflection profiling, *Tectonophysics*, **388**, 85–102, doi:10.1016/j.tecto.2004.07.024.
- Luth, S. W., and E. Willingshofer (2008), Mapping of the post-collisional cooling history of the Eastern Alps, *Swiss J. Geosci.*, **101**, suppl. 1, 207–223, doi:10.1007/s00015-008-1294-9.
- Madritsch, H., S. M. Schmid, and O. Fabbri (2008), Interactions between thin- and thick-skinned tectonics at the northwestern front of the Jura fold-and-thrust belt (eastern France), *Tectonics*, **27**, TC5005, doi:10.1029/2008TC002282.
- Michalski, I., and M. A. Soom (1990), The Alpine thermo-tectonic evolution of the Aar and Gotthard massifs, central Switzerland: Fission track age on zircon and apatite and K-Ar mica age, *Schweiz. Mineral. Petrogr. Mitt.*, **70**, 373–387.
- Most, P. (2003), Late Alpine cooling histories of tectonic blocks along the central part of the TRANSALP-Traversal (Inntal-Gadertal): Constraints from geochronology, Ph.D. thesis, 97 pp., Univ. Tübingen, Tübingen, Germany.
- Nivière, B., and T. Winter (2000), Pleistocene northwards fold propagation of the Jura within the southern Upper Rhine Graben: Seismotectonic implications, *Global Planet. Change*, **27**, 263–288, doi:10.1016/S0921-8181(01)00070-4.
- Pfiffner, A. O. (1986), Evolution of the north Alpine foreland basin in the Central Alps, *Spec. Publ. Int. Assoc. Sedimentol.*, **8**, 219–228.
- Pfiffner, O. A., F. Schlunegger, and S. J. H. Buiter (2002), The Swiss Alps and their peripheral foreland basin: Stratigraphic response to deep crustal processes, *Tectonics*, **21**(2), 1009, doi:10.1029/2000TC900039.
- Philippe, B., B. Colletta, E. Deville, and A. Mascle (1996), The Jura fold-and-thrust belt: A kinematic model based on map-balancing, in *Peri-Tethys Memoir 2: Structure and Prospects of Alpine Basins and Forelands*, edited by P. A. Ziegler and F. Horvath, *Mem. Mus. Natl. Hist. Nat.*, **170**, 235–261.
- Piana, F. (2000), Structural setting of western Monferato (Alps-Apennines junction zone, NW Italy), *Tectonics*, **19**, 943–960, doi:10.1029/2000TC900013.
- Pieri, M., and G. Groppi (1981), Subsurface geological structure of the Po Plain, Italy, *CNR Rep. 414*, Cons. Naz. delle Ric., Rome.
- Rahn, M. (2005), Apatite fission track ages from the Adula nappe: Late stage exhumation and relief evolution, *Schweiz. Mineral. Petrogr. Mitt.*, **85**, 233–245.
- Reinecker, J., M. Danišik, C. Schmid, C. Glotzbach, M. Rahn, W. Frisch, and C. Spiegel (2008), Tectonic control on the late stage exhumation of the Aar Massif (Switzerland): Constraints from apatite fission track and (U-Th)/He data, *Tectonics*, **27**, TC6009, doi:10.1029/2007TC002247.
- Rosenberg, C. L., and S. Schneider (2008), The western termination of the SEMP Fault (Eastern Alps) and its bearing on the exhumation of the Tauern Window, in *Tectonic Aspects of the Alpine-Dinaride-Carpathian System*, edited by S. Siegesmund, B. Fügenshuh, and N. Froitzheim, *Geol. Soc. Spec. Publ.*, **298**, 197–218, doi:10.1144/SP298.10.
- Rosenberg, C. L., J.-P. Brun, F. Cagnard, and D. Gapsis (2007), Oblique indentation in the Eastern Alps: Insights from laboratory experiments, *Tectonics*, **26**, TC2003, doi:10.1029/2006TC001960.
- Rubatto, D., J. Hermann, A. Berger, and M. Engi (2009), Protracted fluid-induced melting during Barrovian metamorphism in the central Alps, *Contrib. Mineral. Petrol.*, doi:10.1007/s00410-009-0406-5.
- Schlunegger, F. (1999), Controls of surface erosion on the evolution of the Alps: Constraints from the of the adjacent foreland basins, *Int. J. Earth Sci.*, **88**, 285–304, doi:10.1007/s005310050265.
- Schlunegger, F., and G. Simpson (2002), Possible erosional control on lateral growth of the European central Alps, *Geology*, **30**, 907–910, doi:10.1130/0091-7613(2002)030<0907:PECOLG>2.0.CO;2.
- Schlunegger, F., and S. Willett (1999), Spatial and temporal variations in exhumation of the central Swiss Alps and implications for exhumation mechanisms, in *Exhumation Processes: Normal Faulting, Ductile Flow and Erosion*, edited by U. Ring et al., *Geol. Soc. Spec. Publ.*, **154**, 157–179, doi:10.1144/GSL.SP.1999.154.01.07.
- Schlunegger, F., J. Melzer, and G. E. Tucker (2001), Climate, exposed source-rock lithologies, crustal uplift and surface erosion: A theoretical analysis calibrated with data from the Alps/North Alpine

- foreland Basin system, *Int. J. Earth Sci.*, 90, 484–499, doi:10.1007/s005310100174.
- Schmid, S. M., and E. Kissling (2000), The arc of the Western Alps in the light of geophysical data on deep crustal structure, *Tectonics*, 19, 62–85, doi:10.1029/1999TC900057.
- Schmid, S. M., O. A. Pfiffner, N. Froitzheim, G. Schönborn, and E. Kissling (1996), Geophysical-geological transect and tectonic evolution of the Swiss-Italian Alps, *Tectonics*, 15, 1036–1064, doi:10.1029/96TC00433.
- Schmid, S. M., B. Fügenschuh, E. Kissling, and R. Schuster (2004), Tectonic map and overall architecture of the Alpine orogen, *Eclogae Geol. Helv.*, 97, 93–117, doi:10.1007/s00015-004-1113-x.
- Schönborn, G. (1992), Alpine tectonics and kinematic models of the central southern Alps, *Mem. Sci. Geol. Padova*, 44, 229–293.
- Schönborn, G. (1999), Balancing cross sections with kinematic constraints: The Dolomites (northern Italy), *Tectonics*, 18, 527–545, doi:10.1029/1998TC900018.
- Schuessler, S., F. Gueydan, and P. Davy (2005), Brittle-ductile coupling: Role of ductile viscosity on brittle fracturing, *Geophys. Res. Lett.*, 32, L10308, doi:10.1029/2004GL022272.
- Schumacher, M. E., G. Schönborn, D. Bernoulli, and H. P. Laubscher (1996), Rifting and collision in the Southern Alps, in *Deep Structure of the Swiss Alps — Results from the National Research Program 20(NRP 20)*, edited by O. A. Pfiffner et al., pp. 186–204, Birkhäuser, Basel, Switzerland.
- Selverstone, J. (1988), Evidence for east-west crustal extension in the Eastern Alps: Implications for the unroofing history of the Tauern Window, *Tectonics*, 7, 87–105, doi:10.1029/TC007i001p00087.
- Smit, J., J.-P. Brun, and D. Sokoutis (2003), Deformation of brittle-ductile thrust wedges in experiments and nature, *J. Geophys. Res.*, 108(B10), 2480, doi:10.1029/2002JB002190.
- Staufenberg, H. (1987), Apatite fission-track evidence for postmetamorphic uplift and cooling history of the eastern Tauern Window and the surrounding Austroalpine (central Eastern Alps, Austria), *Jahrb. Geol. Bundesanst.*, 130, 571–586.
- Stöckhert, B., M. R. Brix, R. Kleinschrodt, A. J. Hurford, and R. Wirth (1999), Thermochronometry and the microstructures of quartz—A comparison with experimental flow laws and predictions on the temperature of the brittle-plastic transition, *J. Struct. Geol.*, 21, 351–369, doi:10.1016/S0191-8141(98)00114-X.
- Thouvenot, F., et al. (1998), The M_L 5.3 Épagny (French Alps) earthquake of 1996 July 15: A long-awaited event on the Vuache Fault, *Geophys. J. Int.*, 135, 876–892, doi:10.1046/j.1365-246X.1998.00662.x.
- TRANSALP Working Group (2002), First deep seismic reflection images of the Eastern Alps reveal giant crustal wedges and transcrustal ramps, *Geophys. Res. Lett.*, 29(10), 1452, doi:10.1029/2002GL014911.
- Ustaszewski, K., and S. M. Schmid (2007), Latest Pliocene to recent thick-skinned tectonics at the Upper Rhine Graben–Jura Mountains junction, *Swiss J. Geosci.*, 100, 293–312, doi:10.1007/s00015-007-1226-0.
- Vernon, A. J., P. A. van der Beek, H. D. Sinclair, and M. K. Rahn (2008), Increase in late Neogene denudation of the European Alps confirmed by analysis of a fission-track thermochronology database, *Earth Planet. Sci. Lett.*, 270, 316–329, doi:10.1016/j.epsl.2008.03.053.
- Viola, G., N. S. Mancktelow, and D. Seward (2001), Late Oligocene-Neogene evolution of Europe-Adria collision: New structural and geochronological evidence from the Giudicarie fault system (Italian Eastern Alps), *Tectonics*, 20, 999–1020, doi:10.1029/2001TC900021.
- Wagner, G. A., G. M. Reimer, and E. Jäger (1977), Cooling ages derived by apatite fission track, mica K/Ar and Rb/Sr dating: Their uplift and cooling history of the central Alps, *Mem. Ist. Geol.* 30, 27 pp., Univ. Padova, Padua, Italy.
- Walpersdorf, A. S., P. Baize, E. Tregoning, E. Calais, and J.-M. Nocquet (2006), Deformation in the Jura Mountains (France): First Results from Semi-Permanent GPS Measurements, *Earth Planet. Sci. Lett.*, 245, 365–372, doi:10.1016/j.epsl.2006.02.037.
- Wiederkehr, M., R. Bousquet, S. M. Schmid, and A. Berger (2008), From subduction to collision: Thermal overprint of HP/LT meta-sediments in the north-eastern Lepontine Dome (Swiss Alps) and consequences regarding the tectonometamorphic evolution of the Alpine orogenic wedge, *Swiss J. Geosci.*, 101, S127–S155, doi:10.1007/s00015-008-1289-6.
- Willett, S. D. (1999), Orogeny and orography: The effects of erosion on the structure of mountain belts, *J. Geophys. Res.*, 104, 28,957–28,981, doi:10.1029/1999JB900248.
- Willett, S. D., and M. Brandon (2002), On steady states in mountain belts, *Geology*, 30, 175–178, doi:10.1130/0091-7613(2002)030<0175:OSSIMB>2.0.CO;2.
- Willett, S. D., F. Schlunegger, and V. Picotti (2006), Messinian climate change and erosional destruction of the central European Alps, *Geology*, 34, 613–616, doi:10.1130/G22280.1.
- Wölfler, A., C. Dekant, M. Danisik, W. Kurz, I. Dunkl, M. Putis, and W. Frisch (2008), Late stage differential exhumation of crustal blocks in the central Eastern Alps: Evidence from fission track and (U-Th)/He thermochronology, *Terra Nova*, 20, 378–384, doi:10.1111/j.1365-3121.2008.00831.x.

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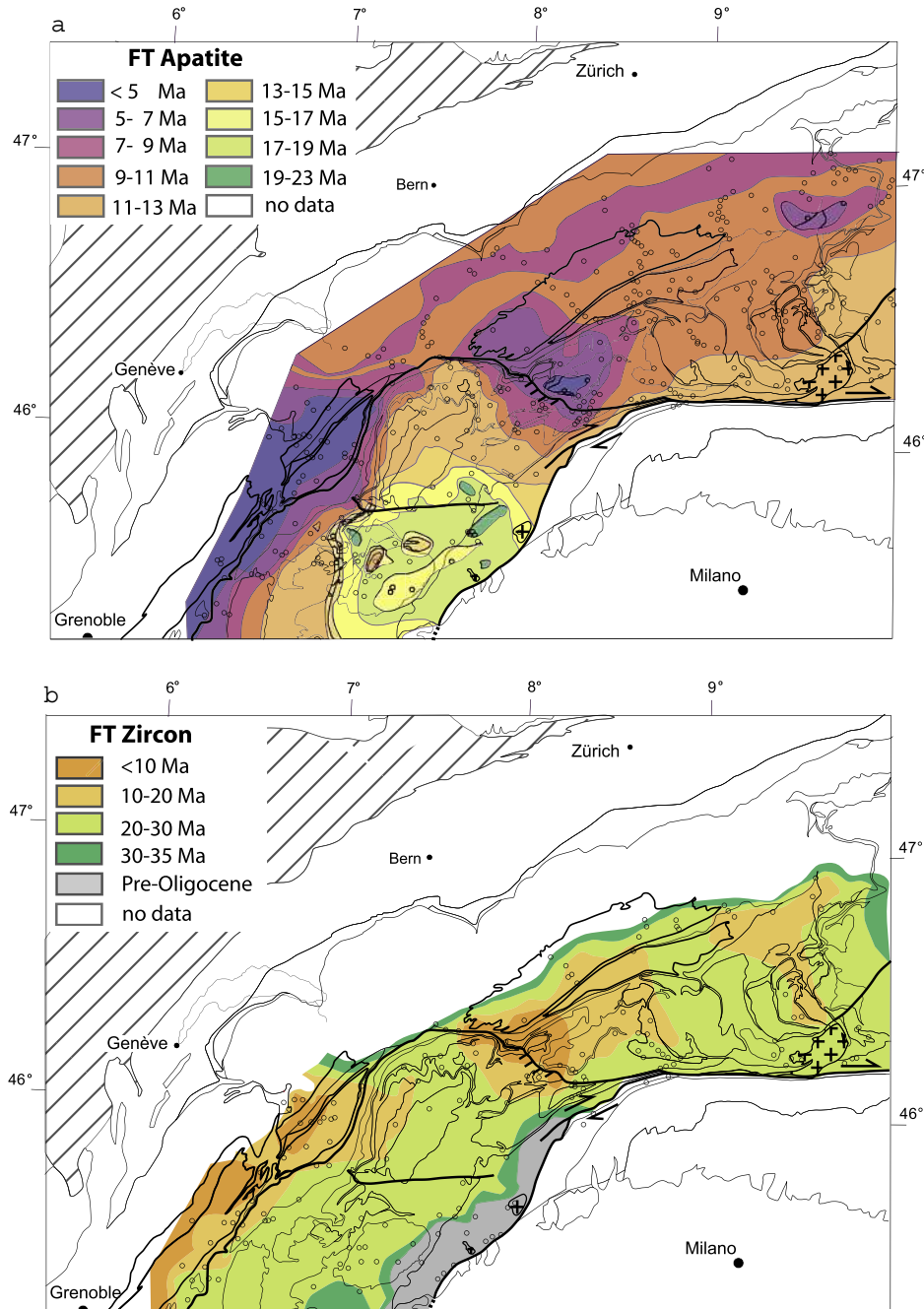


Figure 5. Compiled and contoured ages of fission tracks in zircons and apatites. (a) Apatite fission track ages in the central and Western Alps, redrawn after *Fügenschuh and Schmid* [2003], *Keller et al.* [2006], *Reinecker et al.* [2008], and *Vernon et al.* [2008]. (b) Zircon fission tracks in the central and Western Alps. Sources are the same as in Figure 5a. (c) Zircon fission track ages in the Eastern Alps. Compiled after *Dunkl et al.* [2003], *Fodor et al.* [2008], *Fügenschuh et al.* [1997], *Most* [2003], *Stöckhert et al.* [1999], *Viola et al.* [2001], and *Wölfler et al.* [2008]. Ages are normalized to a height of 1000 m on the base of exhumation rates published and/or calculated from the cited papers. (d) Apatite fission track ages in the Eastern Alps. Compiled after *Dunkl et al.* [2003], *Fodor et al.* [2008], *Foeken et al.* [2007], *Fügenschuh et al.* [1997], *Grundmann and Morteani* [1985], *Hejl* [1998], *Most* [2003], *Staufenberg* [1987], *Stöckhert et al.* [1999], *Viola et al.* [2001], and *Wölfler et al.* [2008]. Ages are normalized to a height of 1000 m on the base of exhumation rates published and/or calculated from the papers quoted above.*

*Caption is correct here. The article as originally published appears online.

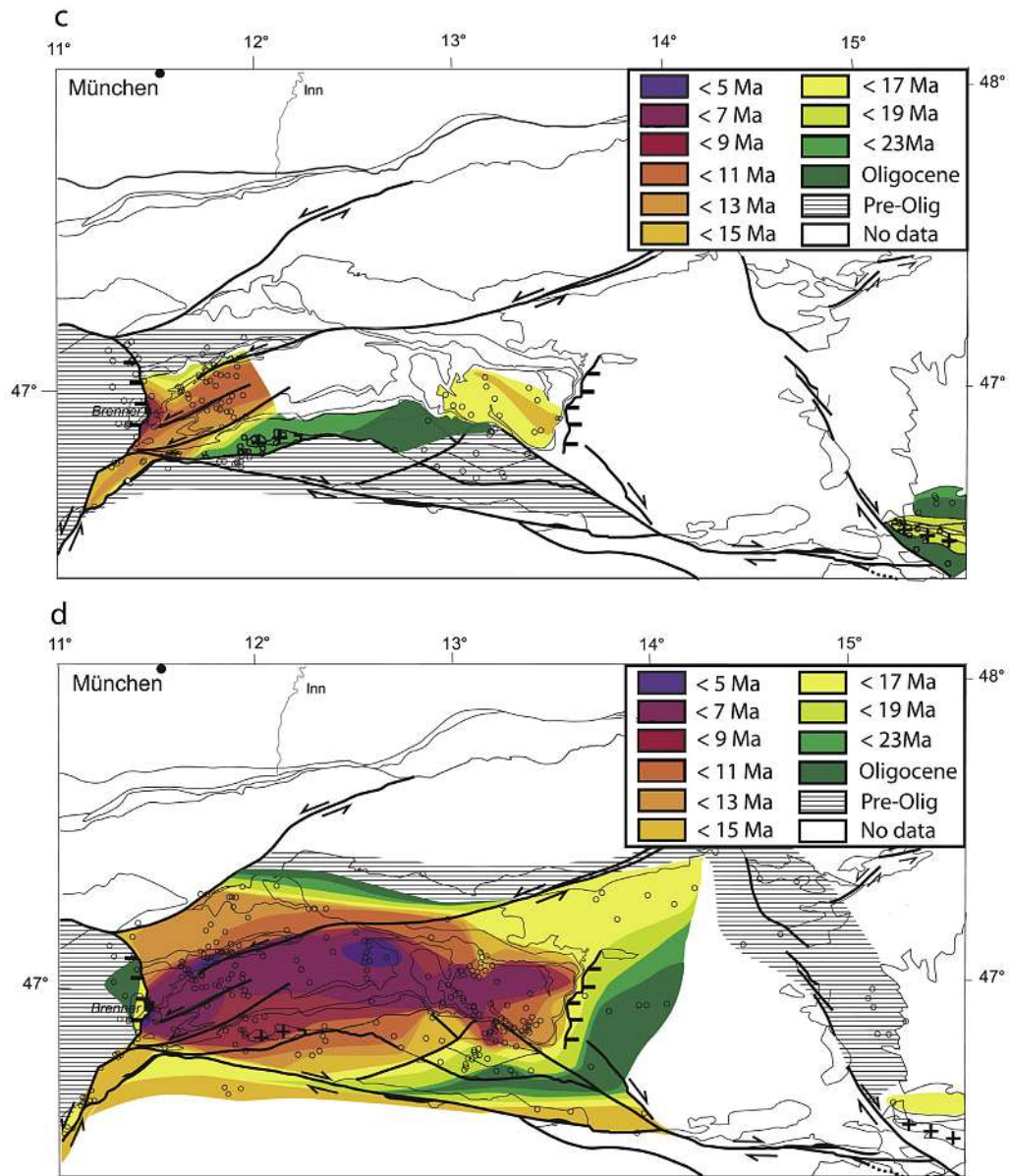


Figure 5. (continued)

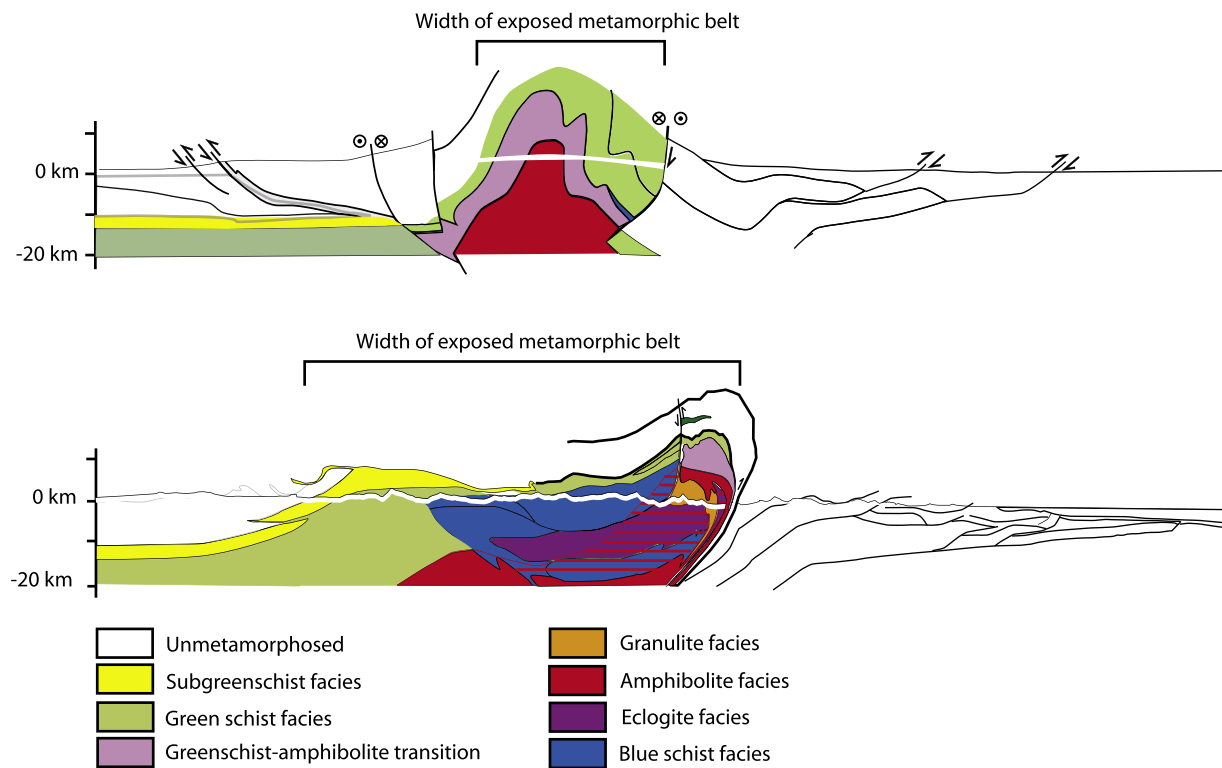


Figure 7. Cross sections of the central and the Eastern Alps showing the distribution of Tertiary metamorphic facies. Simplified after *Bousquet et al.* [2008].